mc82
.8c21d
360
c.2

Geological Survey of Canada
Commission géologique du Canada

BULLETIN 360

NATURAL BACKGROUND RADIATION IN CANADA

Canada

1984

84- 3919 /

BULLETIN 360

NATURAL BACKGROUND RADIATION IN CANADA

R.L. GRASTY
J.M. CARSON
B.W. CHARBONNEAU
P.B. HOLMAN

1984

© Minister of Supply and Services Canada 1984

Available in Canada through

authorized bookstore agents
and other bookstores

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Hull, Québec, Canada K1A 0S9

and from

Geological Survey of Canada
601 Booth Street
Ottawa, Canada K1A 0E8

A deposit copy of this publication is also available
for reference in public libraries across Canada

Cat. No. M42-360-E Canada: $6.00
ISBN 0-660-11564-6 Other countries: $7.20

Price subject to change without notice

Critical Readers

H. Johnson (A.E.C.L., Pinawa)
J. Howieson (E.M.R. Uranium and Nuclear Energy Branch)
L. Lovborg (Riso National Laboratory, Denmark)

Original manuscript submitted: 1982 - 10 - 12
Final version approved for publication: 1983 - 04 - 22

Preface

During the Geological Survey's first hundred years, geologists used traditional mapping methods that relied on ground transportation – by canoe, horse or on foot. With the widespread use of aircraft since 1940s, however, airborne techniques have been developed and these have increased by several orders of magnitude the rate at which information on Canada's landmass and offshore areas is accumulated.

The Geological Survey of Canada has pioneered in the development of airborne survey techniques, particularly, as is discussed in this report, the development of a high sensitivity gamma ray spectrometer system.

In the late 1960s the Survey recognized that a highly sensitive system to measure ground-level changes in radioactivity was needed to support geological mapping and aid uranium exploration. Other uses have since been realized for the system.

OTTAWA, July 1983

R.A. Price
Director General
Geological Survey of Canada

Préface

Au cours des cent premières années d'existence de la Commission géologique du Canada, les géoloques ont utilisé des méthodes de cartographie classiques qui étaient liées aux modes de transport au sol: en canot, à cheval ou encore à pied. Le recours à l'aéronef, fort répandu depuis les années 40, a toutefois engendré des techniques de cartographie aérienne qui ont accéléré formidablement le rythme d'acquisition des données sur la masse continentale et les régions offshore du Canada.

La Commission géologique du Canada a joué un rôle de pionnier dans le domaine de la conception des techniques d'observation aérienne, particulièrement dans la réalisation d'un système de spectrométrie à rayons gamma d'une grande sensibilité, tel qu'en témoigne le présent rapport.

Vers la fin des années 60, la Commission a convenu de la nécessiité de concevoir un système d'observation très sensible, capable de mesuré les variations de radioactivité au sol, pour soutenir la cartographie géologique et aider à la recherche de l'uranium. Il va sans dire que depuis lors, on a trouvé d'autres applications au système.

OTTAWA, juillet 1983

Directeur général de la
Commission géologique du Canada
R.A. Price

ADDENDUM

Further studies on the uranium sensitivities of the two airborne systems have shown that the contribution of uranium to the total exposure rate should be increased from 9 to 17 per cent. This increases the total exposure rate from potassium, uranium and thorium by approximately 10 per cent.

CONTENTS

1 Abstract/Résumé
1 Introduction
3 Terminology and dose relationships
5 The GSC airborne system
5 Production of maps and profiles
5 Removal of background radiation
5 Spectral stripping procedure
5 Altitude correction
5 Conversion of corrected count rate data to ground concentrations
7 The relationship between radioelement concentration and exposure
9 The conversion of airborne data to exposure
12 The relationship between the geological environment and exposure
15 Average summer outdoor exposure rate from terrestrial radiation
15 The population distribution
19 The effect of forest cover
19 Annual outdoor dose from terrestrial radiation
19 The effect of snow
20 Seasonal soil moisture variations
21 Calculation of average outdoor dose-equivalent
21 Additional components of outdoor radiation dose
21 Cosmic radiation
22 Airborne radioactivity
22 The internal radioactivity of the body
23 Estimation of annual dose equivalent
23 The effects of buildings
24 Calculation of annual dose-equivalent
24 Discussion of results
25 Summary and conclusions
26 Acknowledgments
26 References

29 **Appendix** – Radiation exposure rates for areas across Canada

Tables

5 1. Spectral windows used to measure gamma rays
6 2. Radioelement concentration of the Breckenridge calibration range
8 3. Sensitivities of the two GSC spectrometer systems
8 4. Calculated contribution of potassium, uranium and thorium to the exposure rate 1 m above the ground
8 5. Gamma ray exposure rates of the Breckenridge calibration range
9 6. Airborne surveys used in the data compilation
12 7. Mean and standard deviation of the summer outdoor exposure rate
14 8. Percentiles of the summer outdoor exposure rate for each area surveyed
14 9. Radioelement concentrations of different classes of rocks
19 10. Population data used in computing the average summer outdoor exposure rate from terrestrial radiation
20 11. Average monthly soil moisture values in southern Ontario
21 12. Correction factors to be applied to summer outdoor exposure rates to derive annual values
22 13. Annual whole-body dose-equivalents from internal sources of radioactivity
23 14. Average annual Canadian whole-body outdoor dose-equivalent from natural sources of radiation
24 15. Estimated average annual Canadian whole-body dose-equivalents from natural sources of radiation

Figures

2	1.	Radioactivity profiles from Nova Scotia
4	2.	An airborne gamma ray spectrum showing the four energy bands
6	3.	Potassium count-rate variation with aircraft altitude
7	4.	Variation of potassium and thorium count-rate over the Breckenridge calibration range
7	5.	Variation of potassium and uranium count-rate over the Breckenridge calibration range
7	6.	Comparison of ground and airborne potassium measurements
7	7.	Comparison of ground and airborne uranium measurements
8	8.	Comparison of ground and airborne thorium measurements
10	9.	Location of airborne gamma ray spectrometric surveys
11	10.	Distribution of radiation exposure rates for Canada
13	11.	The mean radiation exposure rate (in $\mu R \cdot h^{-1}$) for each area surveyed
15	12.	The relationship between the exposure rates for bedrock and the associated overburden
16	13.	Distribution of plutonic igneous rocks in Nova Scotia
17	14.	Computer-generated exposure rate map of Nova Scotia
18	15.	Distribution of uranium in Canada
22	16.	Variation with altitude of the annual dose equivalent from the ionizing component of cosmic radiation
24	17.	Outdoor exposure rates for some countries

FOREWORD

This paper has been prepared as a contribution to "Radiation in Canada", a multidisciplinary report bringing together the specialized knowledge of several agencies of the government of Canada, the Atomic Energy Control Board, Atomic Energy of Canada Ltd., Department of the Environment, and Department of Energy, Mines and Resources under the leadership of the Radiation Protection Bureau of the Department of Health and Welfare. It is being published as a Geological Survey of Canada Bulletin because the subject of radioactivity in the natural environment is of interest to many geologists, particularly those who have occasion to answer questions from the general public.

The Geological Survey of Canada has been involved in the measurement of natural radiation since 1934 when H.V. Ellsworth made a portable Geiger-Muller counter for the purpose of finding radioactive minerals. In the late 1940s the Survey participated, with the National Research Council, in the trials of some of the first airborne radiometric equipment, commencing with ion-chambers, progressing to multiple Geiger-Muller tubes and then to a small scintillation crystal. The scientific evidence that indicated it might be feasible to construct an airborne gamma ray spectrometer system was provided by the laboratory and field experiments of A.F. Gregory (of GSC) and J.L. Horwood (of Mines Branch) in the late 1950s. The advent of transistorized electronics about that time prepared the way for the instrumentation developments that followed.

The next important step was the construction of the first 4-channel field portable gamma ray spectrometer by R.W. Doig, then a graduate student at McGill University. This was used in 1965 and 1966 to make measurements on rock outcrops in the Elliot Lake area, which were then sampled, and analyzed in the laboratory, to serve as a calibration for the spectrometer. By 1966 the first commercial airborne gamma ray spectrometer systems had appeared on the market, but with the exception of one system developed in the USA for the US Navy, they were of low sensitivity and of little practical value. At this juncture the Geological Survey of Canada decided to go ahead with the development of a high quality airborne system making use of the expertise in nuclear instrumentation possessed by Atomic Energy of Canada Ltd. A joint GSC-AECL project was launched which lasted through 1967-68. This was a period of intensive experimentation, instrument construction and field trials. Many hundreds of ground level measurements were made by P.G. Killeen, J. Carson, J. Parker and M. Husband using portable gamma ray spectrometers. These were complemented by a series of airborne experiments with laboratory equipment mounted in a large helicopter, hovering for prolonged periods at different heights whilst parameters were varied and count rates recorded. This somewhat hazardous set of experiments, performed by Q. Bristow, D.K. Donhoffer and C.J. Thompson established beyond question the design specifications, especially the detector volume, that would be required to construct an operationally effective gamma ray spectrometer system. This spectrometer system was to operate in a fixed-wing aircraft flying at 200 kilometres per hour and 120 metres altitude, with the ability to distinguish ground level changes of 0.25% K, 1.0 ppm eU and 2.0 ppm eTh over successive 150 m sampling lengths. These requirements were met by the summer of 1969. Meanwhile early in 1968 a series of artificial calibration pads had been constructed at Ottawa airport to serve as a means of calibrating both ground portable and stationary aircraft-mounted spectrometers.

AVANT-PROPOS

Le présent document, préparé en vue d'être intégré au rapport multidisciplinaire intitulé "Radiation in Canada" regroupe, sous les auspices du Bureau de la radioprotection du ministère de la Santé et du Bien-Être social, les connaissances spécialisées de plusieurs organismes du gouvernement, soit la Commission de contrôle de l'énergie atomique, l'Energie atomique du Canada Ltée, le ministère de l'Environnement et le ministère de l'Énergie, des Mines et des Ressources. Il est publié sous forme de bulletin de la Commission géologique du Canada, le rayonnement dans les milieux naturels étant un sujet qui intéresse de nombreux géologues, particulièrement ceux qui ont l'occasion de répondre aux questions du grand public.

La Commission géologique du Canada participe à l'évaluation du rayonnement naturel depuis 1934, année où M. H.V. Ellsworth a fabriqué un compteur Geiger-Muller portatif destiné à détecter des minéraux radioactifs. Vers la fin des années 40, la Commission s'est jointe au Conseil national de recherches pour mettre à l'essai certains des premiers instruments radiométriques aéroportés, depuis les chambres d'ionisation, jusqu'aux tubes compteurs Geiger-Muller multiples et à un petit compteur à scintillation. A la fin des années 50, les expériences sur le terrain et en laboratoire effectuées par MM. A.F. Gregory (de la Commission géologique du Canada) et J.L. Horwood (de la Direction des mines) ont prouvé scientifiquement qu'il serait possible de construire un spectromètre à rayons gamma aéroporté. A peu près au même moment, la venue des transistors a pavé la voie à la mise au point de nouveaux instruments.

La fabrication du premier spectromètre à rayons gamma portatif à quatre canaux par M. R.W. Doig, alors inscrit aux études supérieures à l'Université McGill, a constitué une autre étape importante de l'évolution de cette science. L'instrument a été utilisé en 1965-1966 pour prendre des mesures au-dessus d'affleurements rocheux de la région d'Elliot Lake, dont des échantillons ont été analysés en laboratoire afin de servir d'étalon au spectromètre. Vers 1966, les premiers spectromètres à rayons gamma aéroportés de valeur commerciale ont fait leur apparition sur le marché, mais, à l'exception d'un appareil mis au point aux États-Unis pour la marine américaine, ils étaient très peu sensibles et peu utiles. C'est à cette époque que la Commission géologique du Canada a décidé d'entreprendre la mise au point d'un appareil aéroporté de grande qualité en ayant recours aux compétences de l'Énergie atomique du Canada Ltée en matière d'instrumentation nucléaire. Un projet conjoint de la CGC et de l'EACL, a alors vu le jour pour prendre fin en 1967-1968. Il s'est agit d'une période d'expérimentation, de mise au point et d'essais sur le terrain intensifs. MM. P.G. Killeen, J. Carson, J. Parker et M. Husband ont pris des centaines de mesures au sol à l'aide de spectromètres à rayons gamma portatifs. Les mesures ont été complétées par une série d'expériences réalisées à l'aide de matériel de laboratoire installé à bord d'un gros hélicoptère, qui restait stationnaire pendant des périodes prolongées à différentes hauteurs, de façon à permettre de varier les paramètres et d'enregistrer les taux de comptage. Bien que quelque peu dangereuses, les expériences de MM. Q. Bristow, D.K. Donhoffer et C.J. Thompson ont permis d'établir une fois pour toute les spécifications relatives à la conception, particulièrement quant au volume du détecteur, d'un spectromètre à rayons gamma efficace. L'appareil devait pouvoir fonctionner à partir d'un aéronef à voilure fixe volant à 200 km/h, à une altitude de 120 m, et être capable de détecter des changements au niveau du sol de 0,25 % K, 1,0 ppm eU et 2,0 ppm eTh sur des distances d'échantillonnage successives de 150 m. A l,été de 1969, on avait réussi à satisfaire à toutes ces exigences. Entre temps,

Later that year the problem of calibrating fixed-wing airborne gamma ray spectrometer systems was solved by searching for and selecting a large flat area of uniform radioactivity located in the Ottawa River valley.

These successive steps are recounted because this was the first time that a new airborne geophysical system had been designed from the outset with the intention of measuring ground-level geochemical concentrations from the air. Considerably more work than has been outlined here was required in order to bring this intent to fruition, and the authors of this paper played a major part in accomplishing this. However, it would be inappropriate not to acknowledge the part also played by the designer of the GSC airborne instrumentation, Q. Bristow, for making it possible to obtain consistently high quality data in a very demanding operational environment.

The original purpose of the Geological Survey of Canada in developing an airborne gamma ray spectrometer system was to support geological mapping. It was also clear from the outset that a device with the sensitivity and stability required for mapping purposes would be an effective tool for uranium exploration. Subsequently, as a consequence of this emphasis upon data quality, the basic method has proved to be suitable for the measurement of the water-equivalent of snow cover, the search for low-levels of radioactive contaminants both on the ground and in the air, and as reported in this paper, the radiation levels of the natural environment.

The detailed considerations which enter into the determination of radioelement concentrations in the natural environment, and the relationship between these concentrations and the radiation dose received by people in their everyday living and working environment, is a topic which necessarily bridges several conventional fields of study, and has not previously been attempted by researchers with an earth science training. The authors of this paper have brought new insight into the problems involved.

au début de 1968, une série de plaques de calibrage artificiel avaient été construites à l'aéroport d'Ottawa, afin de calibrer tant les spectromètres au sol que ceux installés dans des aéronefs. Plus tard, au cours de la même année, le problème du calibrage des spectromètres à rayons gamma installés à bord d'aéronefs à voilure fixe a été résolu, grâce à la recherche et au choix d'une grande zone plane à niveau de rayonnement uniforme dans la vallée de la rivière des Outaouais.

Pour la première fois, un nouvel appareil géophysique aéroporté était conçu dès le départ dans le but de mesurer, du haut des airs, des concentrations géochimiques au niveau du sol. Bien entendu les étapes décrites ci-dessus ne représentent qu'une infime partie des efforts qu'il a fallu déployer pour en arriver à des résultats concrets. Les auteurs du présent document ont d'ailleurs joué un rôle important dans la réalisation de cet objectif.

Toutefois, on ne peut passer sous silence le rôle qu'a aussi joué le concepteur de l'instrument aéroporté de la Commission géologique, M. Q. Bristow, grâce auquel il est possible d'obtenir constamment des données de grande qualité dans un milieu opérationnel très exigeant.

A l'origine, la Commission géologique du Canada voulait mettre au point un spectromètre à rayons gamma aéroporté pour aider à la réalisation des cartes géologiques. Il était aussi entendu au départ qu'un instrument doté d'un degré de sensibilité et de stabilité assez élevé pour servir à la cartographie serait un outil très efficace pour trouver de l'uranium. Par la suite, en raison de l'importance qui avait été accordée à la qualité des données, la méthode de base a pu servir à mesurer l'équivalent en eau de la couverture de neige, à chercher les contaminants radioactifs de faible niveau, tant dans l'air qu'au sol et, ainsi que souligné dans le présent document, à mesurer les niveaux de rayonnement naturel.

Les considérations détaillées dont il faut tenir compte pour déterminer la concentration des radio-éléments dans le milieu naturel et le lien entre ces concentrations et la quantité de rayonnement à laquelle les gens sont exposés dans leur milieu de travail et leur vie de tous les jours doivent nécessairement faire l'objet d'études touchant plusieurs domaines. Les chercheurs qui ont une formation en sciences de la Terre n'ont pas encore attaqué la question, mais les auteurs de ce document ont donné de nouveaux aperçu aux problèmes en jeu.

A.G. Darnley
Director,
Resource Geophysics and
Geochemistry Division.

Directeur
Division de la géophysique
et de la géochimie appliquées,
A.G. Darnley.

NATURAL BACKGROUND RADIATION IN CANADA

Abstract

Published airborne gamma ray survey data from 33 areas of Canada were used to compile information on the average ground level exposure from natural radiation. The exposures at ground level were calculated from the surface concentrations of potassium, uranium and thorium.

The highest levels of radioactivity were found in northern Canada and were generally related to granitic rocks; the lowest levels with the Athabasca sandstone.

Summer outdoor exposure rates have a population-weighted average of 3.7 ± 2.3 $\mu R \cdot h^{-1}$, of which 48 per cent originated from potassium, 43 per cent from the thorium series and 9 per cent from the uranium series. This low level of radioactivity, compared to worldwide data, has resulted from erosion of a geologically old continental crust in which radioactivity decreases with depth.

When seasonal variations of soil moisture and snow cover are considered, the annual population-weighted average outdoor exposure rate decreases to 2.8 ±1.7 $\mu R \cdot h^{-1}$ corresponding to an annual outdoor dose-equivalent of 150 ± 90 μSv.

Factors increasing the annual outdoor dose-equivalent are cosmic radiation (320 ± 30 μSv) and the internal radioactivity of the body (190 μSv). Using the ratio between indoor and outdoor values for worldwide published data, the average annual Canadian whole-body dose-equivalent from all sources of natural radiation is estimated to be 690 ± 130 μSv.

Résumé

Des données publiées provenant de levés aériens par rayons gamma effectués dans 33 régions du Canada ont été utilisées pour compiler les renseignements sur le niveau d'exposition moyen au rayonnement naturel, au niveau du sol. Ce niveau d'exposition a été calculé à partir des concentrations au sol en potassium, en uranium et en thorium.

Les plus hauts niveaux de radioactivité étaient généralement liés à des roches granitiques qui se trouvent dans le Nord canadien; les niveaux les plus faibles ont été enregistrés dans le grès de l'Athabasca.

L'été, les taux d'exposition à l'extérieur, pondéré en fonction de la population, sont en moyenne de 3,7 ± 2,3 $\mu R \cdot h^{-1}$, dont 48 % provient du potassium, 43 % de la série du thorium et 9 % de la série de l'uranium. Ce faible niveau de radioactivité, par rapport au reste du monde, est dû à l'érosion d'une croûte continentale ancienne au point de vue géologique, où la radioactivité décroît en fonction de la profondeur.

Si l'on tient compte des variations saisonnières relatives à l'humidité du sol et à la couverture neigeuse, le taux moyen annuel d'exposition à l'extérieur, pondéré en fonction de la population, n'est plus que de 2,8 ± 1,7 $\mu R \cdot h^{-1}$, ce qui correspond à un équivalent de dose annuelle à l'extérieur de 150 ± 90 μSv.

Les facteurs qui peuvent causer l'augmentation de l'équivalent de dose annuelle sont le rayonnement cosmique (320 ± 30 μSv) et la radioactivité interne du corps (190 μSv). En effectuant le rapport entre les valeurs intérieures et extérieures à partir des données mondiales publiées, la moyenne canadienne annuelle provenant de toutes les sources de rayonnement naturel est évaluée à 690 ± 130 μSv.

INTRODUCTION

The major source of radiation exposure to man arises from the natural environment. This natural radiation is therefore frequently used as a standard for comparing additional sources of man-made radiation such as those produced by medical sources of x-rays, atomic weapons fallout, nuclear power generation and radioactive waste disposal. To assess the significance of these additional sources of man-made radiation the levels of the natural background radiation and its variation must be known.

Natural radiation exposure originates from both internal and external sources. Internal sources comprise naturally occurring radioactive elements such as ^{40}K and the gas ^{222}Rn which are taken into the body. External sources of radiation originate from cosmic rays and natural radioactive elements, principally ^{40}K and decay products in the uranium and thorium decay series occurring in the ground, in building materials and in the air. This external radiation can vary considerably depending on such things as the geological environment, type of living accommodation, and elevation above sea level.

The decay of natural radionuclides produces alpha particles, beta particles, and gamma radiation. Alpha particles can only travel a few centimetres through the air and are absorbed at the skin surface. Beta particles can travel a metre or so through the air and are absorbed by 1 to 2 cm of water or human tissue. Gamma rays, on the other hand, can travel several hundred metres through the air. Cosmic radiation is highly penetrating and can travel down through the earth's atmosphere to reach ground level.

The lungs and respiratory tract receive a much greater radiation dose than the rest of the body from alpha and beta sources present in the air. Apart from the lungs and the surface of the body, which to some extent is protected by

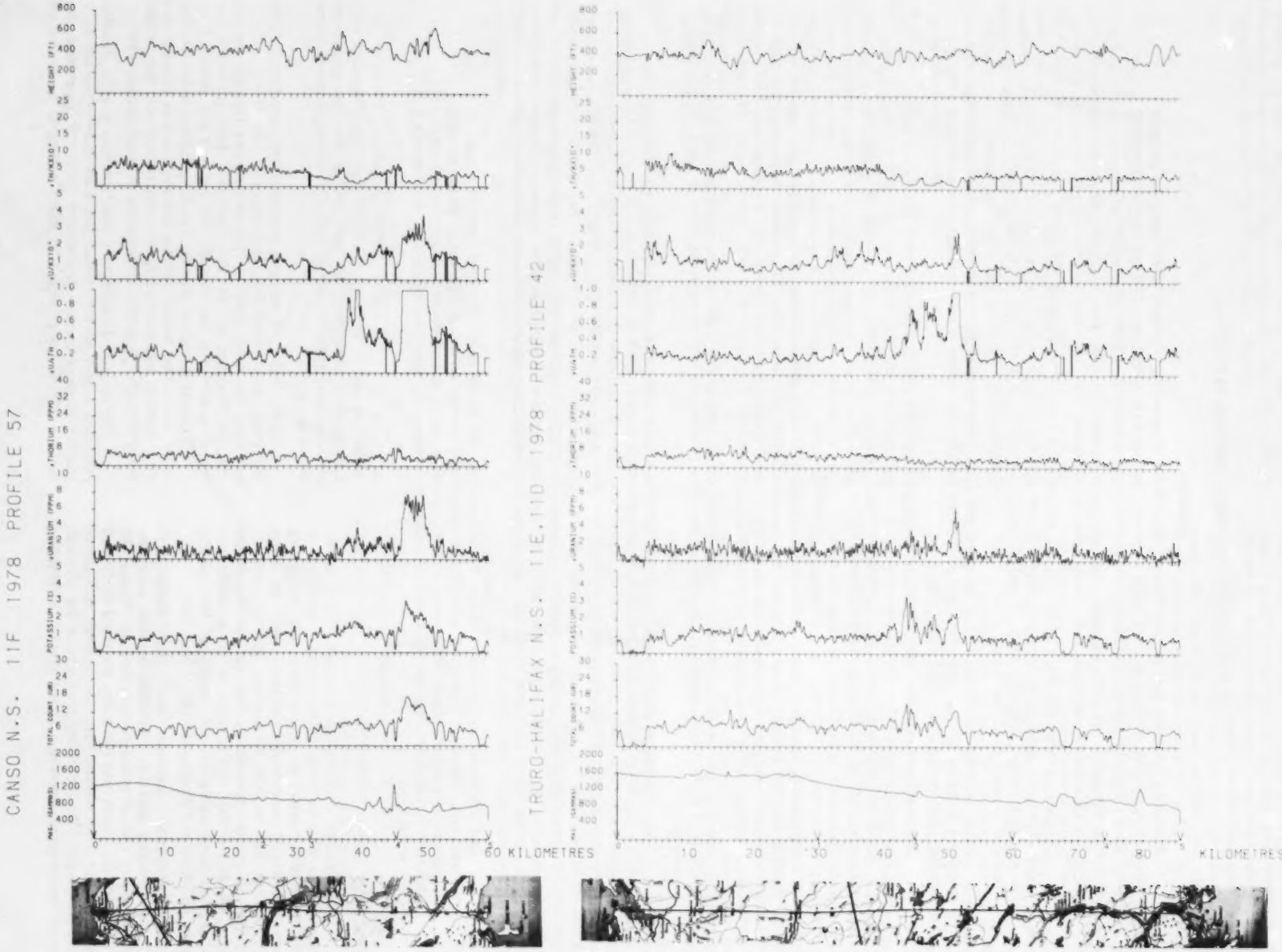

Figure 1. *An example of radioactivity profiles from Nova Scotia (Figures 4A and 4B in Geological Survey of Canada Open File 789).*

clothing, the natural radiation we receive is due almost entirely to gamma radiation and cosmic radiation. This report only considers the effects of gamma radiation and cosmic radiation on the whole body and is not concerned with alpha and beta particles which affect specific parts of the body.

Measurements of natural background radiation have been performed in many parts of the world using a variety of different techniques. These techniques have involved the use of ionization chambers as well as portable and airborne scintillometers. Laboratory analyses of the radioactive elements in soil samples have also been used to estimate the average radiation exposure in several different countries. In comparing worldwide results problems frequently arise. The results of Herbst (1964) for Switzerland as reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 1977) show one of the highest radiation levels reported for any country in the world. These results, however, were made with an ionization chamber and include a 35 per cent contribution from atomic weapons fallout. Since the radiation from fallout has now decayed to negligible levels compared to natural radioactivity, these results should be modified accordingly.

Because of the variability of ground radioactivity from place to place, with any form of ground survey it is difficult to carry out a representative sampling on a country wide basis. This is particularly true in large countries such as Canada or the United States.

In the United States, estimates of natural radiation levels have been made by Oakley (1972) and the National Council on Radiation Protection and Measurements (1975) who used airborne surveys of radioactivity near nuclear facilities. These Aerial Radiological Measurements Surveys (ARMS) were conducted by the United States Geological Survey and EG & G, Inc. for the United States Atomic Energy Commission between 1958 and 1963 and covered 25 areas representing approximately 30 per cent of the population. Because of the large area covered, surveys of this nature provide a far superior method of estimating radiation levels than do ground surveys with a limited number of measurements. The Aerial Radiological Measurements Surveys, however, were scintillometer surveys and could not distinguish between atomic weapons fallout and the radioactivity from potassium and the uranium and thorium decay series. In 1962 and 1963 radiation levels from weapons fallout was around 50 per cent of the natural terrestrial values (Oakley, 1972). The accuracy of the results from the individual Aerial Radiological Measurements Surveys is therefore controlled by the accuracy of the estimation of the fallout during the time the survey was carried out. In addition no systematic calibration procedure was adopted to relate the airborne radioactivity measurements to ground level values. For the more recent airborne gamma ray spectrometer surveys operating under the United States National Uranium Reconnaissance Program (NURE), considerable attention has been paid to the problems of calibration. This involved the construction of large radioactive concrete calibration pads (Ward, 1978) and the selection of an airborne test range with accurately known concentrations of potassium, uranium, and thorium (Geodata International Inc., 1977).

In Canada measurements of radiation exposure at a few selected sites are reported on a routine basis by the Radiation Protection Bureau of the Department of National Health and Welfare through their regular reports. Due to the limited number of sites involved, these measurements have not been included in this report.

In 1967 the Geological Survey of Canada (GSC) commenced an airborne gamma ray spectrometer survey program. This program was designed specifically for estimating ground concentrations of potassium, uranium and thorium to aid in geological mapping and uranium exploration (Darnley, et al., 1969). To deal with the problems of calibration large radioactive calibration pads were constructed at Uplands Airport, Ottawa (Darnley, 1970; Grasty and Darnley, 1971) and an airborne test range was established at Breckenridge, 30 km northwest of Ottawa (Charbonneau and Darnley, 1970). This 10 km test range was systematically sampled to determine its potassium, uranium, and thorium concentrations (Grasty and Charbonneau, 1974).

Airborne gamma ray surveys have now been completed in many parts of Canada and are published as Geological Survey of Canada Geophysical Series maps and Open File reports. These published radioactivity data are presented in the form of contour maps of the concentrations of the three radioelements, as well as individual profiles along aircraft flight lines. Total radioactivity data, which represent all gamma radiation above an energy of 0.41 MeV, are also presented as well as the ratios of the three radioelements for use in mineral exploration. Two such profiles from a survey carried out in Nova Scotia are shown in Figure 1.

This report shows how these airborne data can be used to estimate the outdoor radiation exposure from potassium, uranium and thorium at the surface of the ground. The data are then used to derive an average summer outdoor radiation exposure for each area surveyed and for that part of Canada covered by these surveys. The average annual outdoor radiation dose to the Canadian population was then computed. In this computation seasonal soil moisture fluctuations, and the shielding effect of snow and forest cover were considered as well as additional components of natural radiation from cosmic radiation, atmospheric radon and the internal radioactivity of the body.

The average annual radiation dose to the Canadian population, taking into consideration that most people spend a large percentage of their time indoors, is also discussed. The indoor radiation dose was derived from the outdoor summer value making use of the indoor-to-outdoor ratio from worldwide published data.

TERMINOLOGY AND DOSE RELATIONSHIPS

Units of radioactivity can be confusing even to the practicing health physicist. In this section we explain the various units used in a straightforward manner which we hope will be clear to the average scientific reader who is not a specialist in the field of radiation.

For almost all fields of science a unit of a physical measurement such as temperature, density etc. uniquely defines a particular property of a material. An ionizing radiation field, however, cannot in general be defined uniquely since it can consist of radiation with a complete range of energies and angular distributions. One way of comparing radiation fields is by means of an ionization chamber which measures the quantity of electrical charge released in a gas through absorption of the radiation. This type of measurement is most useful for the health physicist since it may be related to the physical damage that will occur in living cells.

The radiation intensity at a given place is termed its 'Exposure' (E) and is measured by its ability to produce ionization at that place; the unit of exposure is the roentgen (R). One roentgen is defined as the quantity of X radiation or gamma radiation that produces one electrostatic unit of charge of either sign in 1 mL of air at standard temperature and pressure.

In 1956 a unit of radiation, which applied to any form of ionizing radiation, was adopted. This unit of 'absorbed energy' or 'dose' is the energy imparted by ionizing radiation to 1 gram of any material, at the particular point of interest. The unit of absorbed dose is the 'rad' (radiation absorbed dose) which is deposition of an energy of 100 ergs per gram. In expressing the absorbed dose, the particular absorbing material under consideration must always be given.

Environmental radiation measurements are normally presented as absorbed dose rates in air or as exposure rates. The relation between the air absorbed dose rate (D_a) and exposure rate is given by:

$$D_a = aE \qquad (1)$$

where a has the value 0.869 rad$\cdot R^{-1}$.

In this paper all the original data have been compiled and presented in exposure rate units of roentgens per hour ($R \cdot h^{-1}$).

The health physicist is concerned with radiation dose absorbed by the body. Exposure may be converted directly to absorbed dose through the use of a simple conversion factor as in equation (1). This factor takes into consideration the gamma ray energy distribution as well as the geometry and attenuation characteristics of the body. With this direct approach, many of the potentially confusing factors (shielding factors, backscatter factors etc.), which have been developed to solve the gamma ray transport problem, need not be considered.

O'Brien (1978) has calculated the conversion factors between exposure and absorbed dose for various organs and tissues of the body. The relationship between exposure and whole-body dose (D) measured in rads, is given by:

$$D = 0.6E \qquad (2)$$

O'Brien (1978) also showed that the potassium, uranium and thorium energy spectra are almost identical indoors and outdoors and therefore the same relationship will hold for both indoor and outdoor exposure. The dose to the red bone marrow, lungs and gonads, which are generally of interest to the health physicist, can be calculated using the same conversion factor of 0.6 rad$\cdot R^{-1}$.

Different types of radiation cause different effects in biological tissues. For this reason, in comparing the effects of radiation on living systems, a derived unit, the roentgen equivalent man or rem is used. One rem is the dose from any radiation that produces biological effects in man equivalent to one rad of x-rays. The dose in rems is the product of the dose in rads and a factor called the quality factor which depends on the Relative Biological Effectiveness (RBE) of the radiation considered. This unit of dose is commonly called dose-equivalent (D.E). Therefore

$$\text{D.E. (rems)} = \text{RBE} \times \text{rads} \qquad (3)$$

x-rays and gamma rays, which are the principal concern in this report, have an RBE value of 1.

In recent years quantities used in radiation protection have more commonly been expressed in System International units; these SI units are the Gray (Gy) and the Sievert (Sv).

The Gray is the unit of absorbed dose corresponding to the rad and is the energy imparted by ionizing radiation to material corresponding to one joule per kilogram. The relation between the gray and the rad is:

$$1 \text{ Gy} = 100 \text{ rad} = 1 \text{ J} \cdot \text{kg}^{-1}$$

The Sievert is the SI unit for dose-equivalent corresponding to the rem, the relation being given by

$$1 \text{ Sv} = 100 \text{ rem}$$

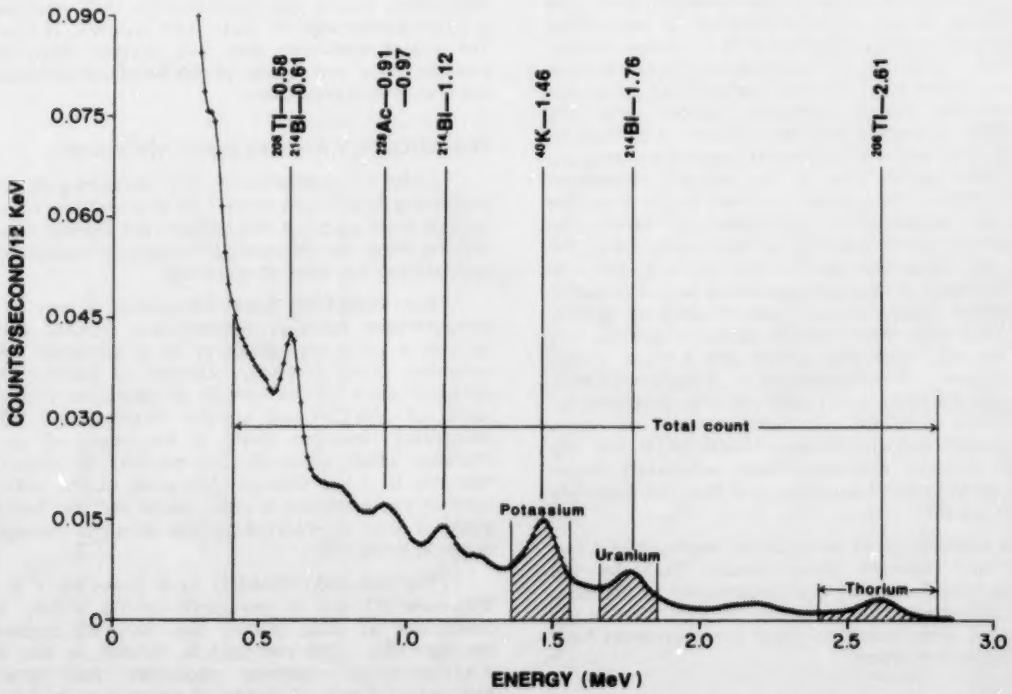

Figure 2. *An airborne gamma ray spectrum showing the four energy bands (potassium, uranium, thorium, and total count).*

In order to compare our results with published data presented in the old units, the practice in this report will be to quote values in SI units, followed by the old units in brackets.

THE GSC AIRBORNE SYSTEM

Prior to 1978 the volume of the airborne gamma ray detectors flown by the Geological Survey of Canada was approximately 50 L of sodium iodide (thallium activated) distributed in twelve 22.9 x 10.2 cm crystals. The detector array was maintained at 38°C in thermally insulated boxes to minimize spectral drift. Pulses from the detectors were fed into a 128 channel analyser from which four energy windows could be selected and the pulses accumulated in four scalers. Figure 2 shows a typical gamma ray spectrum recorded at the normal survey altitude of 120 m. Gamma ray peaks at 2.61 MeV, 1.76 MeV, and 1.46 MeV representing ^{208}Tl in the thorium decay series, ^{214}Bi in the uranium decay series, and ^{40}K respectively can be readily distinguished. These particular gamma rays have generally been accepted as most suitable for the measurement of thorium, uranium and potassium because they are relatively abundant and being high in energy are not appreciably absorbed in the air. The energy windows used to monitor these gamma rays are shown in Table 1. The total count window is recorded since it reflects general lithological variations and is useful in geological mapping. The accumulated counts in these windows were recorded digitally on magnetic tape together with details of aircraft altitude, navigational information and manually inserted operational information. Total count data with its higher count rate were normally recorded every 0.5 seconds whereas the three radioelement windows were recorded every 2.5 seconds.

In 1978 the spectrometer system was upgraded to incorporate a NOVA minicomputer for the recording and analysis of 256 channels of gamma ray information from 0.2 to 3.0 MeV (Bristow, 1979). The package of twelve cylindrical detectors was also changed to twelve prismatic detectors 10.2 x 10.2 cm in cross-section which were 40.6 cm long. This detector configuration has approximately the same volume as that used previously but is packaged more efficiently. The 256 channels of gamma ray data, recorded once a second, were used for accurate energy calibration of the spectrum by monitoring the position of the prominent potassium peak. The windows shown in Table 1, however, were still used to convert the airborne data to ground radioelement concentration.

PRODUCTION OF MAPS AND PROFILES

In order to relate the airborne count rates from the three windows to radioelement concentrations of the ground, four distinct data processing steps are necessary:

the removal of background radiation;

the spectral stripping procedure;

altitude correction; and

the conversion of the corrected count rate data to ground concentration.

Removal of Background Radiation

Three sources of background radiation exist in any airborne radioactivity measurement: the radioactivity of the aircraft and its equipment; cosmic radiation; and radioactivity in the air arising from daughter products of radon gas in the uranium decay series.

Table 1. Spectral windows used to measure gamma rays

Element Analyzed	Isotope Used	Gamma ray Energy (MeV)	Energy Window (MeV)
Potassium	^{40}K	1.46	1.37 – 1.57
Uranium	^{214}Bi	1.76	1.66 – 1.86
Thorium	^{208}Tl	2.62	2.41 – 2.81
TOTAL COUNT			0.41 – 2.81

The technique adopted by the Geological Survey has been to remove the effect of these three sources of background radioactivity simultaneously, by utilizing measurements over water (Darnley et al., 1969). Provided the water body is sufficiently wide and deep the radioactivity measured will be the total background contribution from all three sources. Fortunately, in most of Canada, lakes are abundant and the background values can be updated frequently during the course of the survey.

Spectral Stripping Procedure

Due to the characteristics of the airborne gamma ray spectrum measured by sodium iodide detectors, gamma rays originating from one particular radioelement may be detected in any of the three windows. To correct for this "cross-talk", a spectral stripping procedure must be carried out. This is achieved by determining the gamma ray spectra of the respective radioelements through the use of large radioactive concrete calibration sources which were constructed at Uplands Airport in Ottawa (Grasty and Darnley, 1971). The stripping procedure used to derive the corrected counts in each window that originate from the respective radioelement has been described by Grasty (1976).

Altitude Correction

One of the factors that affects the number of gamma rays detected per second in each window is the altitude of the aircraft above the ground. In the range of altitudes normally encountered in airborne survey operations the stripped and background-corrected count rate in each window (N) is found experimentally to be related to the aircraft altitude (H) by a simple exponential expression of the form:

$$N = Ae^{-\mu H} \qquad (4)$$

where A and μ are constants (Darnley et al., 1969; Kogan et al., 1971; Burson, 1973).

Figure 3 shows the stripped and background-corrected potassium count rate variation with aircraft altitude over the GSC airborne gamma ray spectrometer calibration range at Breckenridge about 30 km west of Ottawa (Charbonneau and Darnley, 1970). The exponential curve given by equation (4) is also shown. This curve is used to correct the count rates in each window for deviations from the planned survey altitude.

Conversion of corrected count rate data to ground concentrations

From the measured ground radioelement concentration of this calibration range the sensitivity of the airborne gamma ray spectrometer in terms of counts per unit time per unit concentration of potassium, uranium, and thorium may be determined at the nominal survey altitude, thus allowing the ground concentration to be evaluated over an unknown area.

To determine the ground level concentrations of the GSC airborne calibration range, 70 soil samples were collected at seven sites along the 10 km length of the strip (Grasty, 1975). These samples were then sealed in metal cans, stored for 4 weeks to allow the gamma ray activity of ^{214}Bi to reach equilibrium, and analyzed in the laboratory by gamma ray spectrometry for potassium, uranium and thorium. These results are presented in Table 2, together with the results of a detailed ground gamma ray spectrometer survey carried out with a portable spectrometer calibrated on the radioactive concrete calibration pads at Uplands Airport in Ottawa (Charbonneau and Darnley, 1970).

In the case of potassium and thorium the field and laboratory measurements show good agreement. The uranium laboratory assays, however, are considerably higher than the field measurements. These results can readily be explained by a loss of ^{222}Rn from the surface soil of the calibration strip and a corresponding decrease in the ^{214}Bi activity. Radon losses of up to 40 per cent are not unusual for the clay material that is characteristic of the Breckenridge strip (Barretto et al., 1972). In the case of the laboratory assays, the radon and associated ^{214}Bi activity is allowed to build up and reach equilibrium because the cans are sealed and the radon gas cannot escape.

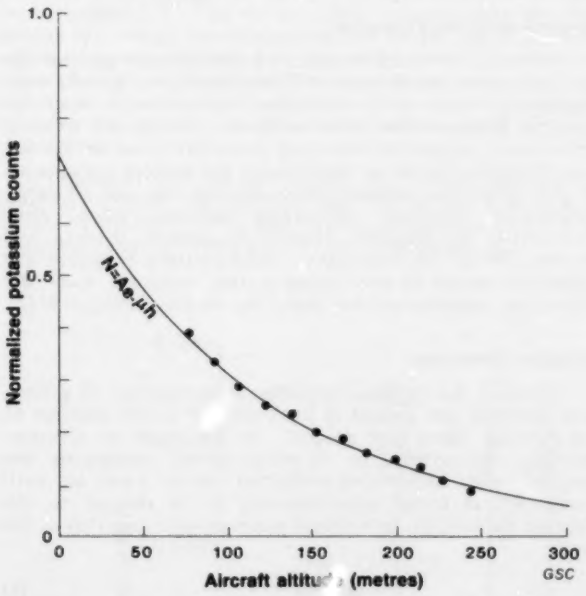

Figure 3. *Potassium count-rate variation with aircraft altitude.*

Table 2. Radio-element concentration of the Breckenridge airborne calibration range

Type of Measurement	Number of Analyses	Potassium (Per cent)	Uranium* (ppm)	Thorium* (ppm)
Laboratory (Sealed can assay)	70	2.03 ± 0.04	0.92 ± 0.09	7.70 ± 0.28
Field	27	1.8 ± 0.1	0.5 ± 0.1	8.0 ± 0.4
Assigned Value		2.03 ± 0.04	0.5 ± 0.1	7.70 ± 0.28

*Assuming radioactive equilibrium.

Additional confirmation of significant radon loss from the soil surface is provided in Figures 4 and 5. These figures show the background-corrected and stripped potassium, uranium and thorium count rate variation over the strip for 8 flights carried out at different times over the past three years. The average thorium and potassium count rates show a predictable linear relationship due to changes in the moisture content of the soil. A ten per cent increase in soil moisture content will decrease the gamma ray flux by approximately the same percentage (Kogan et al., 1971). The stripped potassium and thorium count rates had their lowest values when the soil was completely saturated and pools of water were observed along the strip. In contrast to the behaviour of thorium and potassium, the highest stripped uranium count rates were observed when the soil was saturated with water (Figure 5). These results can be readily explained because water in the soil reduces the emanation of radon from the ground allowing the ^{214}Bi gamma ray activity to increase. Similar results have been observed by Stromswold (1978) when the concrete calibration pads at Grand Junction, Colorado, were saturated with water.

In calculating the exposure rate above the ground due to gamma rays emitted by the uranium series it is necessary to know the gamma ray activity of the ground in the state of equilibrium existing at the time of the measurement. Due to variations in the emanation of radon, this is best provided by field gamma ray spectrometer measurements and not by laboratory assays on sealed samples which can indicate an artificially high gamma ray activity. The equivalent uranium concentration of the test strip was therefore assigned the field value of 0.5 ± 0.1 ppm (Table 2). The thorium and potassium laboratory analyses were considered more reliable than the field measurements because of the greater number of samples analyzed (Table 2). In addition, both thorium and potassium measurements are unaffected by sealing the soil samples in the laboratory sample containers.

The need to correlate airborne and ground-level gamma ray measurements was recognized early in the program and data were compared over many different rock types in the Bancroft and Elliot Lake areas of Ontario covering a large range of radioactive concentrations (Darnley and Fleet, 1968). Subsequently 849 ground measurements were made in the Bancroft area with a calibrated portable gamma ray spectrometer over each rock unit on a regular grid (Darnley, 1970; Charbonneau and Darnley, 1970). The airborne measurements were carried out utilizing three, 12.7 x 12.7 cm sodium iodide detectors with a volume of approximately 5 L mounted in a helicopter which hovered at an altitude of 76 m over each rock unit. The helicopter system was subsequently calibrated by flying over the Breckenridge calibration range, using the assigned concentrations (Table 2).

Figures 6, 7 and 8 show the comparison between the ground and airborne results over the 15 rock units. The ground and airborne potassium and thorium results show particularly good agreement, whereas the uranium results show somewhat more scatter. However, as is shown later in this paper, the gamma rays originating from uranium generally have only a small contribution to the total gamma ray exposure rate. Relatively large errors in the airborne uranium measurements therefore have little effect on the calculated total gamma ray exposure rate.

Based on the potassium, uranium, and thorium count rates recorded over the test strip, the sensitivities of the two 50 L airborne systems were evaluated. These results are presented in Table 3, both for the older system using the cylindrical detectors, and the new system with the prismatic detectors. The results for the older system represent an average of fifteen separate flights; in the case of the current system, only three flights were used. The flights in early spring and late fall were rejected because the soil conditions were extremely wet and were not representative of the conditions occurring when the ground spectrometer survey was carried out.

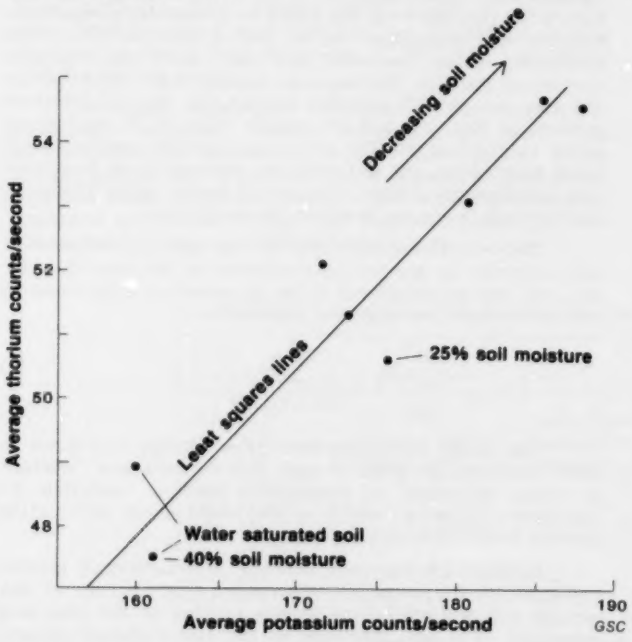

Figure 4. Variation of potassium and thorium count-rate over the Breckenridge calibration range.

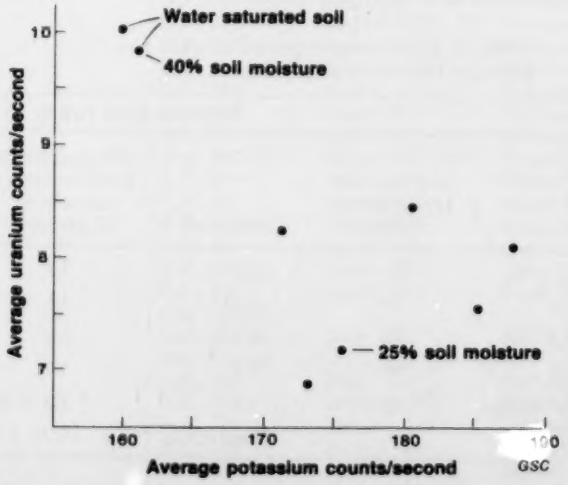

Figure 5. Variation of potassium and uranium count-rate over the Breckenridge calibration range.

THE RELATIONSHIP BETWEEN RADIOELEMENT CONCENTRATION AND EXPOSURE

To evaluate the radiation exposure 1 m above ground caused by a known concentration of the radioelements, the energy distribution of the gamma ray flux of each of the three radioelements must be calculated. This is an extremely complex problem since several hundred gamma ray energies are involved, each with different attenuation coefficients and with multiple scattering occurring both in the ground and in the air. With the advent of high speed computers, however, the energy and angular distribution of both the direct and scattered gamma ray component can now be determined. This has been carried out by Beck and his co-workers at the Environmental Measurements Laboratory in New York (Beck and de Planque, 1968) for the purpose of evaluating the exposure rate from natural gamma radiation and fallout from nuclear weapons tests. Independently, Kirkegaard (1972) and Lovborg and Kirkegaard (1975) have carried out similar

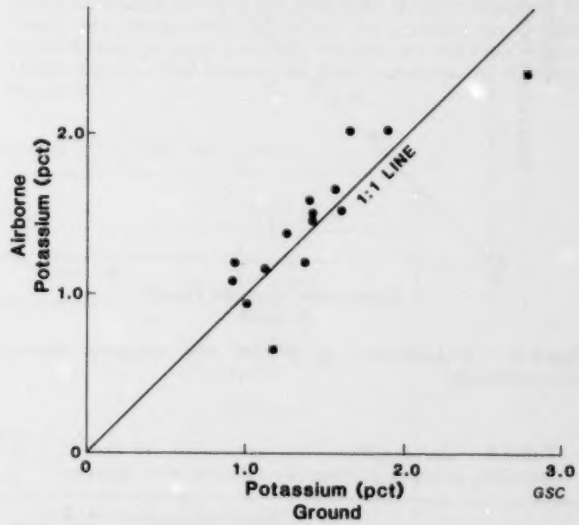

Figure 6. Comparison of ground and airborne potassium measurements.

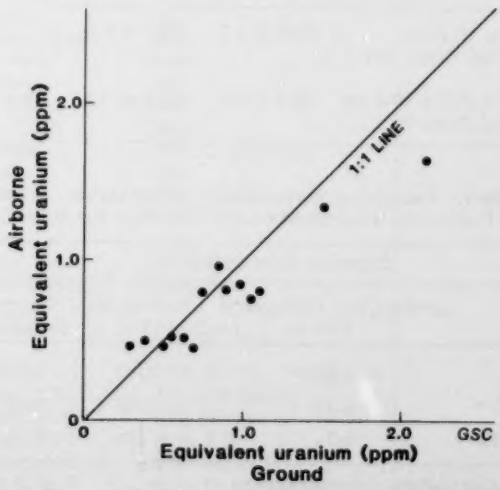

Figure 7. Comparison of ground and airborne uranium measurements.

calculations to aid in the interpretation of gamma ray surveys for exploration and arrived at similar solutions. Both calculations solve the Boltzmaan transport equation for two semi-infinite homogeneous media, one being the ground with a uniform distribution of gamma ray emitters, and the other being the air. Table 4 shows the contribution from potassium, uranium and thorium to the exposure rate 1 m above the ground. The agreement between the results of Beck et al. (1972) and Lovborg and Kirkegaard (1974) is a good indication that the energy distribution of the gamma ray flux can be derived reliably.

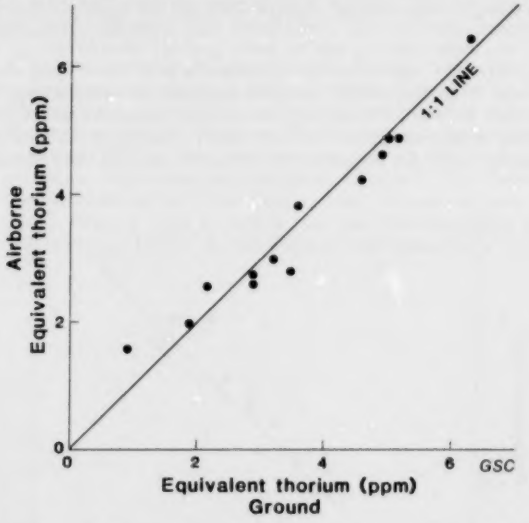

Figure 8. *Comparison of ground and airborne thorium measurements.*

Table 3. Comparison of the sensitivities of the two GSC airborne gamma ray spectrometer systems

	Sensitivity (counts/second)		
System	Potassium Per %K	Uranium Per ppm	Thorium Per ppm
12 22.9 x 10.2 cm Cylindrical Detectors	78.9 ± 4.2	19.1 ± 4.8	6.1 ± 0.4
12 10.2 x 10.2 x 40.6 cm Prismatic Detectors	90.9 ± 1.8	16.2 ± 0.9	7.0 ± 0.1

Table 4. Calculated contribution of potassium, uranium and thorium to the exposure rate 1 m above the ground

	Exposure Rate ($\mu R \cdot h^{-1}$)		
	Lovborg and Kirkegaard 1974	Beck et al. 1972	Assigned Value
1% K	1.52	1.49	1.505
1 ppm U*	0.63	0.62	0.625
1 ppm Th*	0.31	0.31	0.31
*Assuming radioactive equilibrium			

In the fall of 1981 measurements were taken with a Reuter-Stokes ionization chamber at four sites along the airborne gamma ray spectrometer calibration range to verify the relationship between radioelement concentration and radiation exposure presented in Table 4. Radiation measurements were also taken from a boat on the Ottawa River nearby, to estimate the combined background radiation exposure due to cosmic radiation, airborne radioactivity, and any small component of instrument background. Soil moisture measurements were taken at each site because of the dependence of the gamma ray exposure rate on the moisture content of the soil. Utilizing the assigned radioelement concentrations (Table 2) the average exposure rate along the test strip due solely to potassium, uranium and thorium was calculated to be 5.75 ± 0.12 $\mu R \cdot h^{-1}$. This calculated value, however, will vary with the moisture content of the soil. Soil moisture measurements taken during the summers of 1978 and 1979 showed that the soil moisture content of the strip had an average value of 27 per cent of water by dry weight. The ionization chamber measurements were taken when the soil moisture content at all four sites was considerably higher than this average value (Table 5), thereby decreasing the predicted exposure rate.

The reduced exposure rate (E) over soil with W per cent soil moisture by dry weight compared to the value E_o over dry soil, can be considered to be the result of a decrease in radioactive concentration and is given by:

$$E = \frac{100\ E_o}{100 + 1.11\ W} \qquad (5)$$

The factor 1.11 arises because water has 1.11 times as many electrons per gram as most rock material and therefore is more effective in attenuating gamma radiation by Compton scattering, which is the predominant attenuation process above about 0.4 MeV.

Equation (5) does not consider attenuation of gamma radiation by photo-electric absorption which occurs at low energy and depends on the atomic number of the absorbing material. This will decrease as the soil moisture content increases. However, using the computer code of Kirkegaard and Lovborg (1980), equation (5) has been shown to be accurate to better than 1 per cent for soil moisture variations between 0 and 50 per cent and therefore is applicable for all practical purposes.

Table 5. Gamma ray exposure rates of the Breckenridge calibration range

		Exposure Rate ($\mu R \cdot h^{-1}$)	
Site	Soil moisture (Per cent dry weight)	Measured	Normalized to a soil moisture content of 27 per cent
1	37	5.2	5.6
2	39	5.05	5.6
3	75	4.4	6.2
4	38	5.2	5.7
Average	47	5.0	5.8 ± 0.3
		Theoretical Value	5.75 ± 0.12

To compare the calculated and experimental exposure rate measurements, the measured exposure rates were normalized to the average soil moisture content of the strip of 27 per cent utilizing the formula obtained from equation (5).

$$E_{27} = E_W \times \frac{(100 + 1.11 \times W)}{(100 + 1.11 \times 27)} \qquad (6)$$

where E_{27} and E_W are the exposure rates at 27 and W per cent soil moisture (by dry weight), respectively. The original four exposure rate measurements together with the normalized values are presented in Table 5 after subtracting the average background radiations of 5.0 $\mu R \cdot h^{-1}$ measured over the Ottawa River.

The good agreement between the predicted and measured exposure rates demonstrates that the concentrations of potassium, uranium and thorium in the ground, can be used to provide good estimates of gamma ray exposure rates at ground level. Good agreement between measured and calculated radiation exposure rates have also been found by Lovborg and Kirkegaard (1974).

THE CONVERSION OF AIRBORNE DATA TO EXPOSURE

Over 200 airborne gamma ray surveys have been published as GSC Geophysical Series maps and Open File reports. Approximately 70 per cent of these published data have been produced by survey companies through the Federal-Provincial Uranium Reconnaissance program (Darnley, 1976). Because of some calibration problems with the different aircraft systems involved in the program which are presently under investigation, this paper deals only with airborne data obtained by the two GSC systems. These surveys were generally flown at a nominal survey altitude of 120 m at a speed of approximately 56 m per second. Most of the airborne data have been obtained from regional surveys flown at line spacings of 5 km. A significant number of surveys, however, have been flown with line spacings as close as 60 m. These more detailed surveys covered known uranium mining areas such as Elliot Lake, Bancroft or Uranium City, or areas of anomalous radioactivity found during regional surveys. These particular areas of anomalous levels of radioactivity were not used in this study as they would not be representative of the country as a whole. Table 6 lists the published GSC regional survey data analyzed in this report. The location of these survey areas is shown in Figure 9.

Table 6. Airborne surveys at 5 km line spacing used in the data compilation

GSC Publication	Date Published	Area	NTS Area
O.F. 270[1]	June 1975	Burin Peninsula, Nfld.	1M, L (parts)
O.F. 816	January 1982	Sydney, N.S.	11K, 11F (part)
O.F. 429	March 1977	Annapolis-Shelburne, N.S.	21A, B, 20O
Map 35411G[2]			
Map 35511G			11D, E; 11F,
Map 35611G	January 1981	Halifax, N.S.	21H (parts)
Map 35821G			
O.F. 269	June 1975	P.E.I.	11L, 21I (part)
O.F. 271	June 1975	Havre St. Pierre, P.Q.	12L
Map 36031G	August 1979	Mont Laurier, P.Q.	31J
O.F. 331	June 1976	Pembroke, Ont.	31F
O.F. 428	March 1977	Kingston, Ont.	31C
O.F. 262	May 1975	Blind River, Ont.	41J
O.F. 329			
O.F. 330	June 1976	Ignace, Sioux Lookout, Ont.	52G, J
O.F. 315	March 1976	Brochet, Man.	64F
O.F. 316	March 1976	Tadoule Lake, Man.	64J
O.F. 317	March 1976	Whiskey Jack Lake, Man.	64K
O.F. 318	March 1976	Kasmere Lake, Man.	64N
O.F. 319	March 1976	Munroe Lake, Man.	64O
O.F. 309	April 1976	Reindeer Lake, Sask.	64E
O.F.310	April 1976	Wollaston Lake, Sask.	64L
Map 35672G	December 1977	Cypress Hills, Sask.	72F, G, J (parts)
O.F. 311	April 1976	Foster Lake, Sask.	74A
O.F. 314	April 1976	Lloyd Lake, Sask.	74F
O.F. 312	April 1976	Cree Lake, Sask.	74G
O.F. 313	April 1976	Geikie River, Sask.	74H
O.F. 257	April 1975	Fond Du Lac East, Sask.	74P, 64M
O.F. 257	April 1975	Fond Du Lac West, Sask.	74N, O
Map 35574G			
Map 36274G	June 1979	North Eastern Alberta	74E (part), L, M
Map 36374G			
O.F. 101	July 1972	Fort Smith, N.W.T.	75D, E; 75L, 74M (parts)
O.F. 124	January 1973	Yellowknife East, N.W.T.	75L, 85I (parts)
O.F. 124	January 1973	Yellowknife West, N.W.T.	85J, 85I (parts)
O.F. 188	April 1974	Marian River East, N.W.T.	75M, 85P
O.F. 188	April 1974	Marian River West, N.W.T.	85N (part), 85O
O.F. 140	April 1973	Bear Slave East, N.W.T.	86A, H; 86B, G (parts)
O.F. 140	April 1973	Bear Slave West, N.W.T.	86C, F; 86B, G (parts)

[1]Open File
[2]Geophysical Map Series

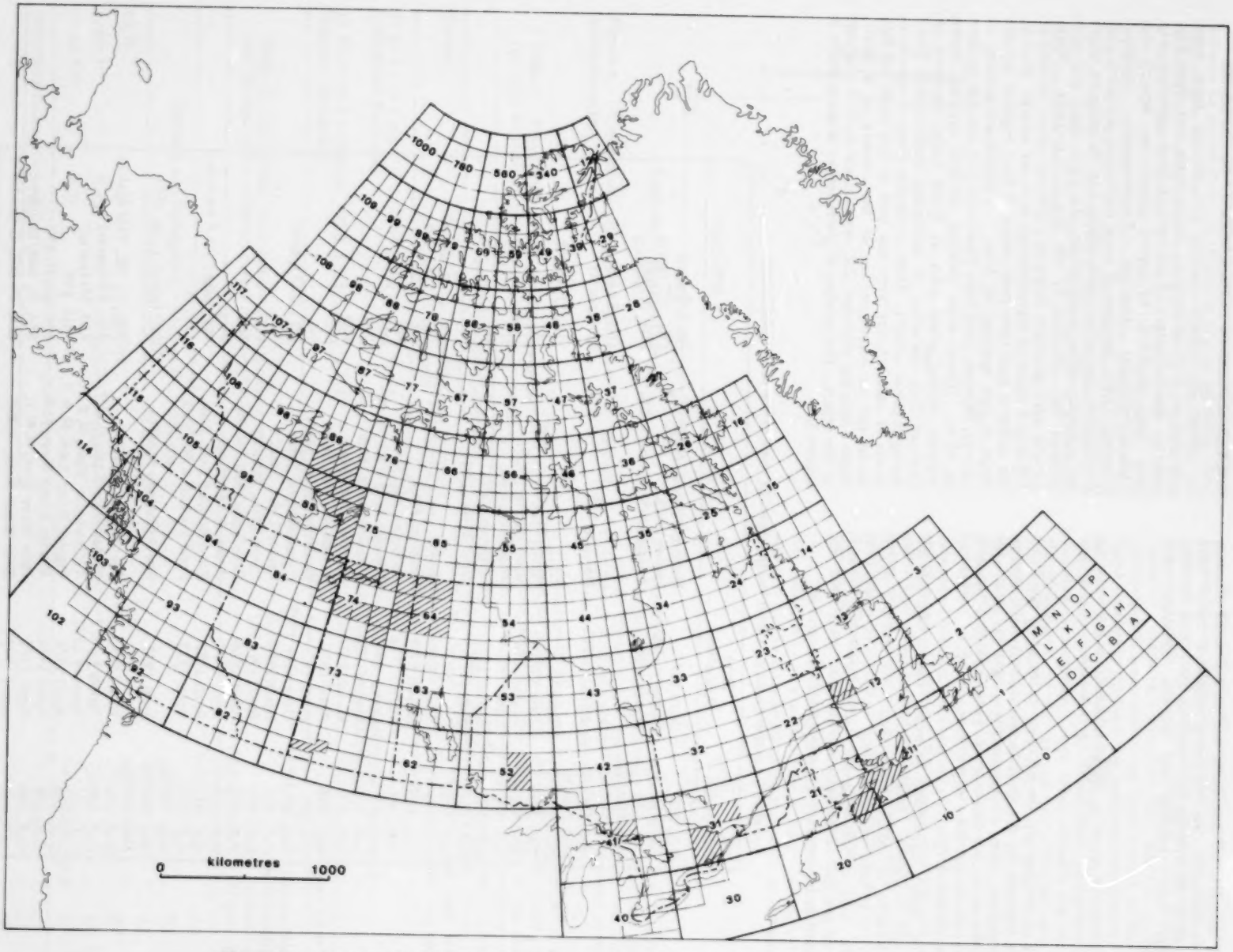

Figure 9. *Location of airborne gamma ray spectrometric surveys at 5 km line spacing carried out using the GSC systems.*

The airborne gamma ray data can be converted to ground level exposure rates either from the airborne profiles (illustrated in Fig. 1) or from the contour maps of the three radioelements. Because the airborne data were obtained from flight lines 5 km apart, the ground is more densely sampled along the flight lines than between them. The original data, therefore, were considerably smoothed along the flight lines to produce contour maps with coherent data from one line to another. With this smoothing the published contour maps, although reflecting regional variations of radioactivity, do not show the same degree of variation as the unsmoothed profile data. Radioactive highs tend to be suppressed and radioactive lows elevated. In order to preserve the real variations in ground level radioactivity the analysis of the airborne data was carried out solely with the profile data.

Most of the published maps and profiles give the system sensitivities that were used at that time for converting the airborne data to ground concentrations of potassium, uranium and thorium. These sensitivities show some variation from year to year. This variation has now been found to relate to changes in the soil moisture content of the Breckenridge calibration strip at the time the calibration flights were carried out (Figs. 4, 5). The analysis of the airborne data, therefore, was based on the original corrected count-rate data and values of the system sensitivities shown in Table 3.

In establishing statistical parameters, such as the mean and standard deviation of the exposure rate for each area, it is necessary to consider that a large fraction of Canada is covered by water. We require radiation measurements relating only to the land surface and therefore any over-water values must be removed in the statistical analysis. Studies of airborne profiles have shown that areas of water, such as lakes, bogs and swamps can be successfully identified from the airborne data by monitoring the potassium concentration. Almost all rocks and soils have potassium concentrations well in excess of 0.25 per cent potassium. Any airborne measurements with potassium concentrations below 0.25 per cent, therefore, were assumed to be associated with over-water measurements and were rejected from the analysis. This technique is used routinely in the processing of the airborne data to identify automatically areas of water so that the background radiation due to cosmic rays, airborne radioactivity and the radioactivity of the aircraft and its equipment may be updated.

Histograms in Figure 10 illustrate the exposure rate for all survey areas in Canada due to potassium, uranium, thorium, and the combined value for all three sources. These histograms were produced by combining histograms for each province that were in turn compiled for each survey area described in Table 6 and shown in Figure 9. These histograms are illustrated in the Appendix as Figure A1 to A9. The histograms were also used to compute the mean and

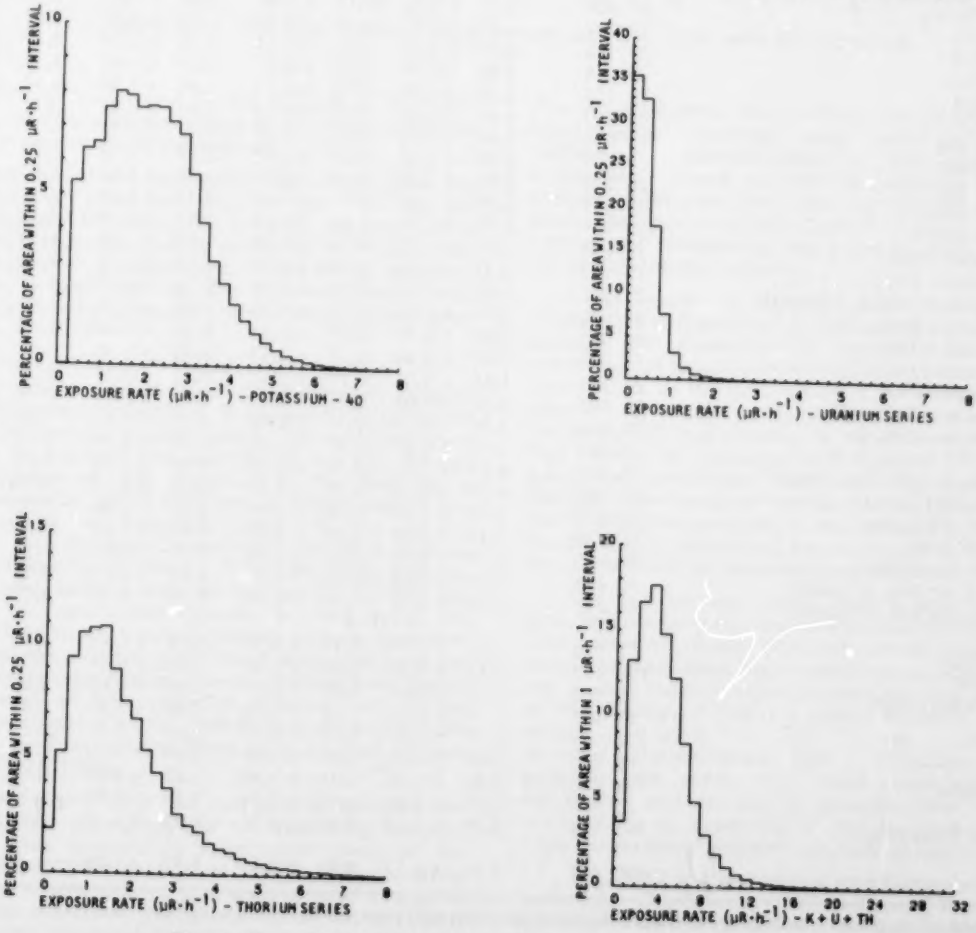
PERCENTAGE OF AREA WITHIN 0.25 μR·h⁻¹ INTERVAL
EXPOSURE RATE (μR·h⁻¹) - POTASSIUM - 40
EXPOSURE RATE (μR·h⁻¹) - URANIUM SERIES
EXPOSURE RATE (μR·h⁻¹) - THORIUM SERIES
PERCENTAGE OF AREA WITHIN 1 μR·h⁻¹ INTERVAL
EXPOSURE RATE (μR·h⁻¹) - K + U + TH

Figure 10. *Distribution of radiation exposure rates for Canada.*

standard deviation of the exposure rate for each survey, for each province, and also for Canada (Table 7). The mean exposure rate for each area is illustrated graphically in Figure 11. Various percentiles of the exposure rate distributions for each survey were also computed (Table 8). A percentile (P) is the radiation level below which lies P percentage of the exposure rate data. For instance these results show that 99 per cent of the entire area of Canada surveyed had an exposure rate of less than 13.3 $\mu R \cdot h^{-1}$.

A gamma ray spectrometer records gamma rays produced by radioactive decay which is a random process. Consequently some of the apparent variation in the calculated exposure rates for each area are the result of statistical fluctuations due to the counting process. The significance of these statistical fluctuations on the standard deviations shown in Table 7 was calculated from the system sensitivity, calibration constants, counting time, and over-water background count rates, assuming each area was uniformly radioactive. The standard deviation of the exposure rate was over-estimated by more than 10 per cent on only six occasions. These six data sets (Table 7) were over-estimated either because they were acquired with a short counting time of one second (one Quebec and two Nova Scotia surveys) or because the ground was homogeneous (the Prince Edward Island and two Saskatchewan surveys).

THE RELATIONSHIP BETWEEN GEOLOGICAL ENVIRONMENT AND EXPOSURE

Beck (1972) has shown that 90 per cent of ground radiation is derived from the top 20 cm. Any airborne gamma ray survey, therefore, will be influenced mainly by

Table 7. Mean and standard deviation of the summer outdoor exposure rate (uncorrected for vegetation)[1]

Area	Number of Measurements	Potassium ($\mu R \cdot h^{-1}$)	Uranium ($\mu R \cdot h^{-1}$)	Thorium ($\mu R \cdot h^{-1}$)	Total ($\mu R \cdot h^{-1}$)
Newfoundland – 1M, 1L (parts)	1 518	1.25 ± 0.77	0.19 ± 0.34	0.96 ± 0.68	2.40 ± 1.80
Nova Scotia – 11K, 11F (part)	33 670	1.40 ± 0.80	0.27 ± 0.49*	1.26 ± 0.73	2.93 ± 1.74
Nova Scotia – 21A, B, 20O	24 673	1.95 ± 0.94	0.37 ± 0.39	1.32 ± 0.63	3.63 ± 1.88
Nova Scotia – 11D, E; 11F, 21H (parts)	86 090	1.63 ± 0.72	0.41 ± 0.43*	1.41 ± 0.60	3.45 ± 1.52
Prince Edward Island – 11L, 21I (part)	8 560	2.00 ± 0.64	0.32 ± 0.31	1.10 ± 0.45*	3.42 ± 1.41
Quebec – 12L	17 307	1.11 ± 0.63	0.17 ± 0.44	0.69 ± 0.61	1.97 ± 1.64
Quebec – 31J	25 862	1.87 ± 0.67	0.27 ± 0.34*	1.03 ± 0.59	3.17 ± 1.51
Ontario – 31F	25 366	1.85 ± 0.67	0.26 ± 0.35	1.08 ± 0.58	3.19 ± 1.55
Ontario – 31C	25 048	2.08 ± 0.91	0.32 ± 0.36	1.14 ± 0.63	3.54 ± 1.81
Ontario – 41J	20 153	2.02 ± 0.83	0.42 ± 0.43	1.89 ± 1.36	4.32 ± 2.52
Ontario – 52G, J	41 102	1.42 ± 0.72	0.21 ± 0.34	1.09 ± 0.81	2.72 ± 1.81
Manitoba – 64F	18 031	2.31 ± 1.22	0.26 ± 0.34	1.74 ± 0.95	4.31 ± 2.39
Manitoba – 64J	19 691	2.57 ± 1.39	0.40 ± 0.40	2.32 ± 1.32	5.29 ± 3.02
Manitoba – 64K	20 878	2.93 ± 1.50	0.48 ± 0.44	3.06 ± 1.67	6.47 ± 3.66
Manitoba – 64N	19 852	3.09 ± 1.46	0.60 ± 0.49	3.37 ± 1.69	7.06 ± 4.05
Manitoba – 64O	18 407	2.76 ± 1.37	0.42 ± 0.43	2.41 ± 1.29	5.59 ± 3.28
Saskatchewan – 64E	16 133	2.37 ± 1.12	0.34 ± 0.38	1.88 ± 1.06	4.59 ± 2.42
Saskatchewan – 64L	18 192	2.35 ± 1.18	0.34 ± 0.39	2.06 ± 1.11	4.75 ± 2.54
Saskatchewan – 72F, G, J (parts)	21 556	2.89 ± 0.45	0.57 ± 0.35	2.38 ± 0.47*	5.84 ± 1.23
Saskatchewan – 74A	21 478	2.44 ± 1.00	0.35 ± 0.36	1.84 ± 0.89	4.63 ± 2.09
Saskatchewan – 74F	15 549	0.62 ± 0.39	0.09 ± 0.33	0.82 ± 0.43*	1.53 ± 1.22
Saskatchewan – 74G	12 599	0.69 ± 0.44	0.10 ± 0.33	0.90 ± 0.50	1.68 ± 1.30
Saskatchewan – 74H	21 350	1.56 ± 1.04	0.22 ± 0.35	1.61 ± 0.91	3.39 ± 2.13
Saskatchewan – 74P, 64M	36 573	2.14 ± 1.03	0.31 ± 0.40	1.51 ± 0.95	3.96 ± 2.39
Saskatchewan – 74N, O	31 420	2.09 ± 1.13	0.34 ± 0.45	1.57 ± 1.05	4.00 ± 2.47
Alberta – 74E (part), L, M	25 985	1.29 ± 1.04	0.29 ± 0.38	1.34 ± 0.96	2.92 ± 2.30
NWT – 75D, E; 75L, 74M (parts)	51 431	2.83 ± 1.33	0.51 ± 0.50	2.94 ± 1.44	6.28 ± 3.99
NWT – 75L, 85I (parts)	30 789	2.58 ± 1.26	0.70 ± 0.57	2.06 ± 1.33	5.35 ± 3.32
NWT – 85J, 85I (parts)	32 573	2.52 ± 1.12	0.72 ± 0.53	2.06 ± 1.26	5.30 ± 2.83
NWT – 75M, 85P	28 759	2.55 ± 1.24	0.62 ± 0.59	2.41 ± 1.61	5.58 ± 3.48
NWT – 85N (part), 85O	31 422	2.74 ± 1.24	0.61 ± 0.50	2.79 ± 1.47	6.13 ± 3.11
NWT – 86A, H; 86B, G (parts)	30 619	2.27 ± 0.81	0.37 ± 0.36	2.44 ± 1.21	5.08 ± 2.22
NWT – 86C, F; 86B, G (parts)	57 810	2.51 ± 1.07	0.47 ± 0.43	2.72 ± 1.31	5.70 ± 2.72
Newfoundland	1 518	1.25 ± 0.77	0.19 ± 0.34	0.96 ± 0.68	2.40 ± 1.80
Nova Scotia	144 433	1.63 ± 0.80	0.37 ± 0.44	1.36 ± 0.64	3.36 ± 1.66
Prince Edward Island	8 560	2.00 ± 0.64	0.32 ± 0.31	1.10 ± 0.45*	3.42 ± 1.41
Quebec	43 169	1.56 ± 0.75	0.23 ± 0.38	0.89 ± 0.62	2.69 ± 1.67
Ontario	111 669	1.77 ± 0.82	0.28 ± 0.37	1.24 ± 0.91	3.30 ± 1.99
Manitoba	96 859	2.74 ± 1.42	0.44 ± 0.44	2.60 ± 1.49	5.78 ± 3.48
Saskatchewan	194 850	2.01 ± 1.16	0.31 ± 0.40	1.65 ± 0.98	3.97 ± 2.43
Alberta	25 985	1.29 ± 1.04	0.29 ± 0.38	1.34 ± 0.96	2.92 ± 2.30
Northwest Territories	263 403	2.59 ± 1.18	0.56 ± 0.51	2.55 ± 1.39	5.69 ± 3.20
Canada	890 446	2.12 ± 1.17	0.40 ± 0.45	1.87 ± 1.24	4.39 ± 2.86

[1]In forested areas these results may be underestimated as much as 15 per cent.

*Indicates the standard deviation is over-estimated (see text).

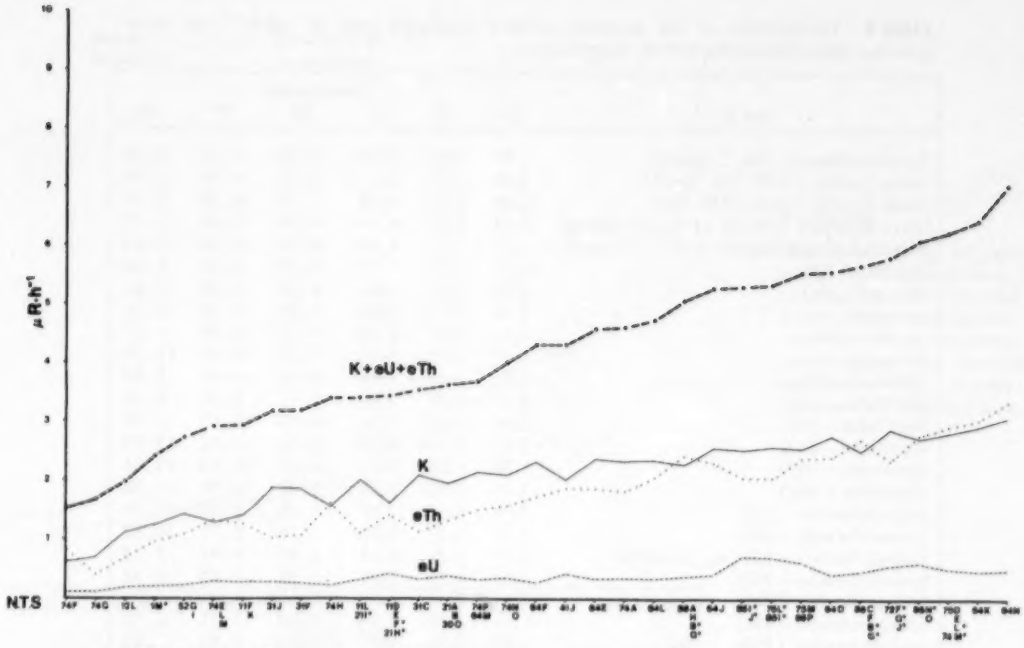

Figure 11. *The mean radiation exposure rate (in $\mu R \cdot h^{-1}$) for each area surveyed.*

the distribution of rock types at the surface of the earth modified by the effect of overburden or soil which generally covers a large percentage of the bedrock.

Many reviews have been published which give the average levels of potassium, uranium and thorium for different classes of rocks. Table 9, adapted from Killeen (1979), illustrates typical values to be found in the major rock types. An average crustal value is also indicated (Taylor, 1964). Generally all three radioelements vary sympathetically with granitic rocks being the most radioactive.

In assessing regional radioactivity patterns it is necessary to consider that the bedrock is generally covered by surficial material (overburden). In Canada this overburden is dominated by glacial till which may or may not be capped by soil. This till will have been eroded from outcrops through glaciation, transported and dispersed in the form of a negative exponential curve with the concentration of the material reaching a maximum close to its source (Shilts, 1976). Soil has been derived from the till or exposed bedrock by weathering processes. The relationship between the radioelement concentration of the glacial till and the bedrock was a fundamental concern in considering the potential usefulness of regional gamma ray spectrometer surveys because the airborne signal which originates from the near surface material would be generally derived from glacial till. Awareness of this potential problem led to the systematic investigation of the radioactivity of outcrop and overburden in the Bancroft and Elliot Lake areas of Ontario (Darnley and Fleet, 1968).

To further investigate the relationship between the radioactivity of the glacial till and the underlying bedrock, 24 test sites were selected in three other areas of the Canadian Shield (Charbonneau et al., 1976). These sites, averaging a few square kilometres in area, covered a range of rock types with associated glacial till cover. In all, more than 2500 in situ measurements of potassium, uranium, and thorium were made with a calibrated portable gamma ray spectrometer. Average values were calculated for the radioelement concentrations of the bedrock and the overburden. Based on their radioelement concentrations, exposure rates were determined for both the bedrock and the overburden using data from Table 4. Figure 12 illustrates the sympathetic relationship that exists between exposure rates for the till and the bedrock.

The results in Figure 12 show that the overburden reflects the radioactivity of the underlying bedrock. This is because the overburden is composed of a substantial percentage of locally derived material (Shilts, 1976). Similar observations on the local nature of the overburden have been observed by Pitkin (1968) in the United States and by Perttunen (1977) in Finland. In areas where the bedrock has high levels of radioactivity, Figure 12 shows that the associated overburden also has high radiation levels. Similarly, low levels of bedrock radioactivity correspond to low levels of radioactivity in the overburden. The overburden has the effect of reducing the amplitude of the variations in the radioactivity of the underlying bedrock.

As can be seen from Table 9 acid intrusive rocks (granites) are generally the most radioactive rock types. The table, however, shows that sedimentary and metamorphic rocks can also have high radioactivity levels. Figures 13 and 14 show the high exposure rates for most of the granites of Nova Scotia. There is a close correlation between areas above $4\ \mu R \cdot h^{-1}$ and the granites of Devonian – Carboniferous age. Although granites are generally the main rock types underlying any broad radioactive anomaly not all granites have high levels of radioactivity as illustrated by the Precambrian granites of Cape Breton Island which do not show an anomalous response.

Figure 15 is a preliminary compilation of airborne data taken from Charbonneau (1982) and shows the distribution of uranium. For this particular map, data produced by survey companies through the Federal – Provincial Uranium Reconnaissance Program (Darnley, 1976) were also included.

Table 8. Percentiles of the summer outdoor exposure rate in $\mu R \cdot h^{-1}$ for each area surveyed (Uncorrected for Vegetation)

Area	Percentiles 25	50	75	90	95	99
Newfoundland – 1M, L (parts)	1.30	2.12	3.24	4.42	5.12	7.18
Nova Scotia – 11K, 11F (part)	2.06	2.73	3.61	4.66	5.59	7.74
Nova Scotia – 21A, 21B, 20O	2.38	3.61	4.79	5.75	6.30	7.39
Nova Scotia – 11D, E; 11F, 21H (parts)	2.63	3.41	4.16	4.94	5.56	6.57
Prince Edward Island – 11L, 21I (part)	2.75	3.50	4.19	4.71	4.89	5.46
Quebec – 12L	1.11	1.72	2.59	3.64	4.49	6.62
Quebec – 31J	2.38	3.14	3.84	4.66	5.08	6.42
Ontario – 31F	2.38	3.19	3.86	4.63	4.96	6.26
Ontario – 31C	2.41	3.47	4.54	5.52	5.99	7.07
Ontario – 41J	2.69	3.75	5.31	7.64	9.10	11.74
Ontario – 52G, J	1.66	2.49	3.46	4.65	5.65	7.95
Manitoba – 64F	2.57	4.28	5.90	7.25	7.98	9.26
Manitoba – 64J	2.96	5.22	7.26	8.93	10.12	12.79
Manitoba – 64K	3.60	6.44	8.93	10.82	12.18	15.70
Manitoba – 64N	4.34	6.60	9.05	12.20	14.43	19.06
Manitoba – 64O	3.36	5.43	7.13	9.28	10.94	15.98
Saskatchewan – 64E	3.04	4.60	5.97	7.38	8.30	10.34
Saskatchewan – 64L	3.04	4.67	6.30	7.78	8.75	10.85
Saskatchewan – 72F, G, J (parts)	5.33	5.84	6.43	6.80	6.93	7.52
Saskatchewan – 74A	3.36	4.73	5.84	6.88	7.65	8.98
Saskatchewan – 74F	1.15	1.52	1.88	2.48	2.83	3.74
Saskatchewan – 74G	1.19	1.59	1.99	2.82	3.35	4.51
Saskatchewan – 74H	1.88	2.96	4.73	6.06	6.83	8.48
Saskatchewan – 74P, 64M	2.50	3.73	4.98	6.52	7.64	10.50
Saskatchewan – 74N, O	2.25	3.80	5.32	6.82	7.91	10.91
Alberta – 74L, M; 74E (part)	1.46	2.32	3.84	5.88	7.16	9.58
NWT – 75D, E; 75L, 74M (parts)	3.90	5.67	7.66	10.55	13.50	21.35
NWT – 75L, 85I (parts)	3.34	4.85	6.53	9.11	11.73	16.85
NWT – 85J, 85I (parts)	3.60	4.94	6.58	8.89	10.37	13.22
NWT – 75M, 85P	3.34	4.92	6.97	10.26	12.48	16.29
NWT – 85N, (part), 85O	4.06	6.15	8.04	9.77	10.96	13.72
NWT – 86A, H; 86B, G (parts)	3.80	5.04	6.36	7.64	8.47	10.30
NWT – 86C, F; 86B, G (parts)	4.07	5.58	7.22	8.91	10.13	12.77
Newfoundland	1.30	2.12	3.24	4.42	5.12	7.18
Nova Scotia	2.42	3.28	4.15	5.05	5.74	6.91
Prince Edward Island	2.75	3.50	4.19	4.71	4.89	5.46
Quebec	1.68	2.62	3.57	4.43	4.94	6.49
Ontario	2.15	3.06	4.08	5.36	6.39	9.24
Manitoba	3.27	5.51	7.68	9.94	11.66	16.08
Saskatchewan	2.04	3.90	5.57	6.72	7.52	9.72
Alberta	1.46	2.32	3.84	5.88	7.16	9.58
Northwest Territories	3.74	5.34	7.13	9.30	11.00	15.84
Canada	2.48	3.93	5.74	7.70	9.23	13.30

N.B. In forested areas these results may be underestimated as much as 15 per cent.

Table 9. Radioelement concentrations of different classes of rocks*

Rock Class	Example	Code	K (%) Mean	K (%) Range	U (ppm) Mean	U (ppm) Range	Th (ppm) Mean	Th (ppm) Range
Acid Extrusives	rhyolite	—	3.1	1 – 6	4.1	1 – 16	11.9	1 – 40
Acid Intrusives	granite	(AI)	3.4	0 – 8	4.5	0 – 30	25.7	0 – 250
Basic Extrusives	basalt	(BE)	0.7	0 – 2	0.8	0 – 3	2.2	0 – 9
Basic Intrusives	gabbro	(BI)	0.8	0 – 3	0.8	0 – 6	2.3	0 – 15
Ultrabasic	dunite	—	0.3	0 – 1	0.3	0 – 2	1.4	0 – 8
Chemical Sedimentary Rocks	gypsum	—	0.6	0 – 8	3.6	0 – 27	14.9	0 – 130
Carbonates	limestone	(C)	0.3	0 – 4	2.0	0 – 18	1.3	0 – 11
Detrital Sedimentary Rocks	sandstone	(DS)	1.5	0 – 10	4.8	0 – 80	12.4	0 – 360
Metamorphosed Igneous Rocks	orthogneiss	—	2.5	0 6	4.0	0 – 150	14.8	0 – 105
Meatmorphosed Sedimentary Rocks	paragneiss	(MS)	2.1	0 – 5	3.0	0 – 53	12.0	0 – 90
Average continental crust			2.1		2.7		9.6	

*Adapted from Table 10C.6 (Killeen, 1979)

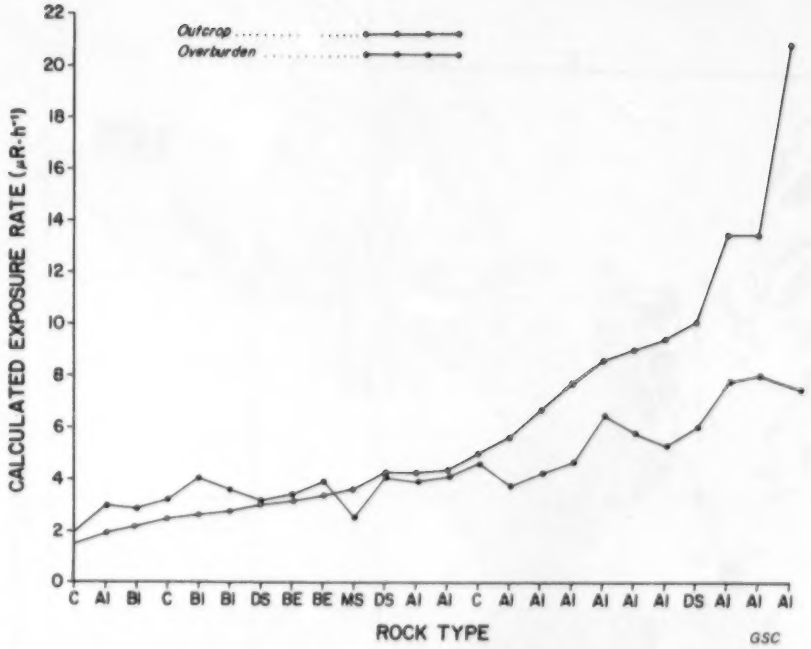

Figure 12

The relationship between the exposure rates for bedrock and the associated overburden for 24 sites as calculated from their potassium, uranium and thorium concentrations. The 24 sites are ordered by increasing potassium concentrations. Codes for each rock type are defined in Table 9.

The sympathetic relationship that generally exists between potassium, uranium and thorium (Fig. 11), suggests that an exposure rate map would show similar patterns.

Many of the more radioactive areas have been investigated on the ground and without exception have been found to be related to granitic rocks with concentrations of uranium and thorium that are several times the crustal average (Charbonneau, 1982). Although the underlying rock type is the prime factor governing radiation levels at the surface of the ground, the soil type and percentage of rock outcrop, can also exert a modifying influence over a particular area.

Seldom is pure rock or glacial till exposed at the surface over a wide area without some soil being developed. North of the treeline the soils are poorly developed with little organic content. These soils will be expected to bear a close relationship to the radioactivity of the underlying bedrock. South of the treeline the soils usually have an organic capping and can be water-satured for long periods of time thereby reducing the surface radioactivity. The trees themselves also attenuate the gamma radiation signal from the ground resulting in a somewhat lower estimate of ground radioactivity than would otherwise be observed.

The Northwest Territories and northern Manitoba have the highest levels of radioactivity in Canada. Much of these areas are above the treeline, have poorly developed soils, and have a high percentage of rock outcrop, which tend to increase the radiation levels. However, the high levels of radioactivity for these areas are principally because the underlying granitic rocks have above average radioactivity.

The histograms in the Appendix (Fig. A1-A7) show the distribution of exposure rates from potassium, uranium and thorium and the total exposure rate for each survey area. Since each area contains assorted rock types covering a range of concentrations which in most cases overlap, it is frequently impossible to see peaks in the histograms corresponding to the major rock units in a survey area. The effect of overburden also tends to smooth differences in the radioactivity levels that may exist between the different rock units. The separation of different rock units can be better seen in map form because of the spatial relationship between the geology and the airborne data which is not considered in the histograms. In certain areas where the geology is simple, however, the histograms can distinguish between rock units which have distinct radioactive signatures. For example, in Figure A10 (in Appendix) the histograms of the potassium and total exposure show two distinct peaks for Saskatchewan. The lower peak relates to the Athabasca sandstone which is extremely low in radioactivity (as indicated in Table 7 for map sheets 74F and G). The upper peak in the histogram relates to crystalline basement rocks which are substantially more radioactive. Similarly in Figure A1 (in Appendix) for Nova Scotia map sheets 21A and B and 20O, the bimodal histogram results from the difference in radioactivity of granitic and metamorphosed sedimentary rock.

AVERAGE SUMMER OUTDOOR EXPOSURE RATE FROM TERRESTRIAL RADIATION

There are two correction factors that must be applied to the calculated exposure rates (Table 7), as derived from the potassium, uranium and thorium concentrations, to convert them to an average summer outdoor value for the Canadian population. These factors relate to the population distribution and the effect of vegetation.

The Population Distribution

The data presented in this report were gathered from airborne surveys flown over relatively unpopulated areas. In addition, a large percentage of the data was gathered in the Northwest Territories where the average exposure rate is significantly higher than the more populated provinces such as Quebec and Ontario (Table 7). Data on the population of each province were taken from the 1981 Canadian Census (Table 10). Together with the average exposure rate of each province as calculated directly from the airborne data (Table 7), the data were used to compute a population weighted summer outdoor exposure rate from terrestrial radiation. This reduced the average summer outdoor exposure rate, derived from the airborne measurements, from $4.4 \pm 2.9\ \mu R \cdot h^{-1}$ to a population weighted summer outdoor average of $3.2 \pm 2.0\ \mu R \cdot h^{-1}$.

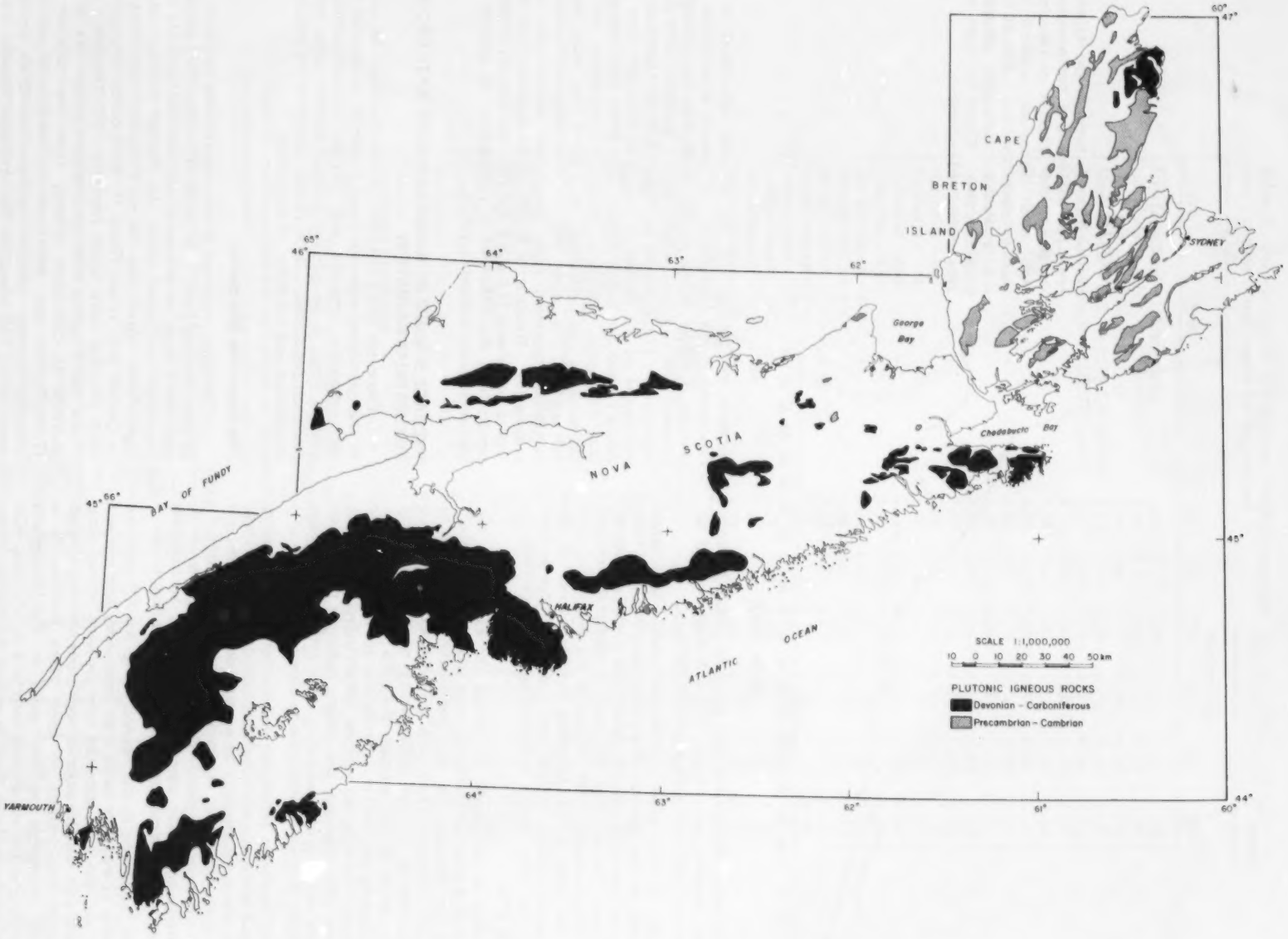

Figure 13. *Distribution of plutonic igneous rocks in Nova Scotia.*

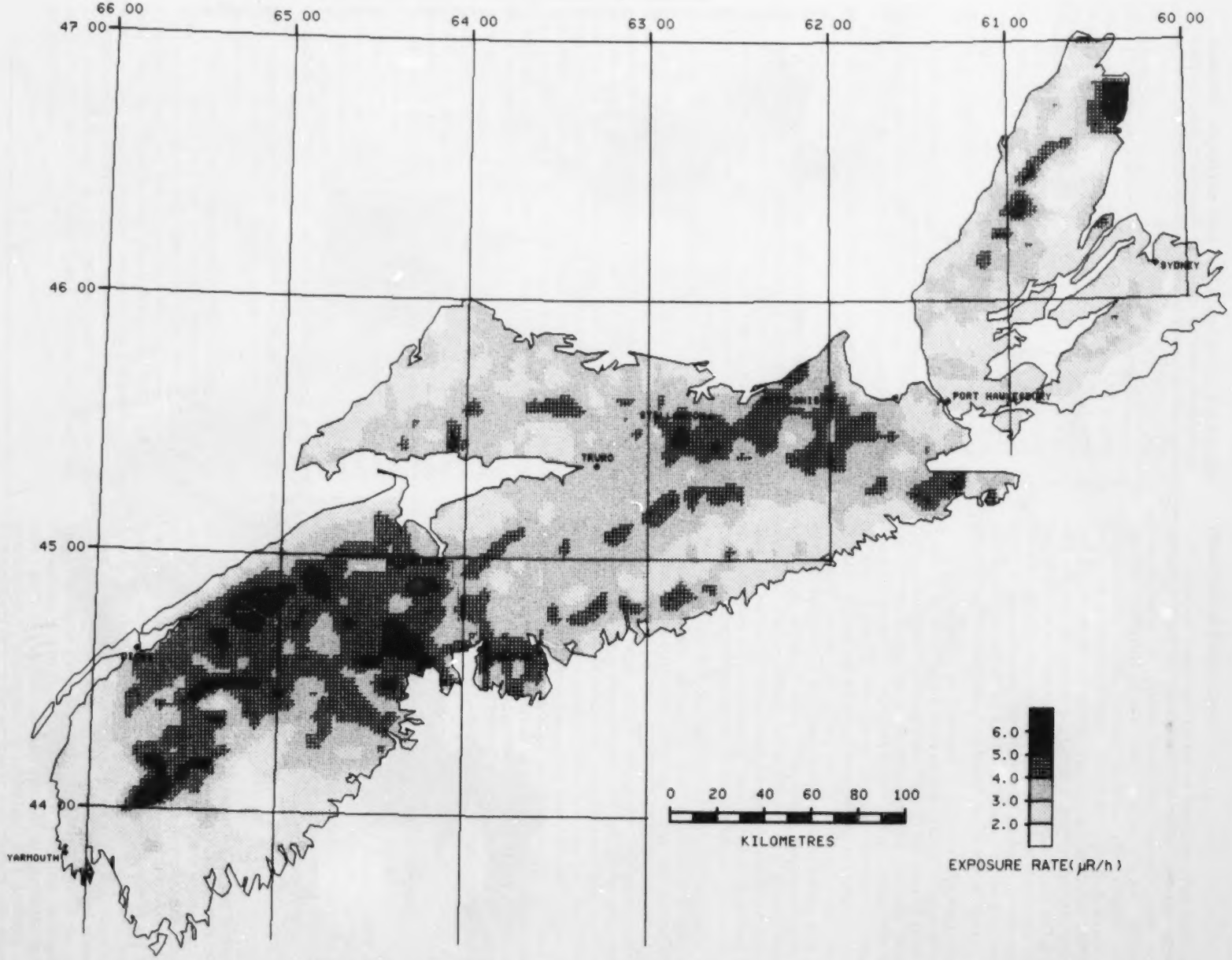

Figure 14. *Computer-generated exposure rate map of Nova Scotia calculated from the ground concentrations of potassium, uranium and thorium.*

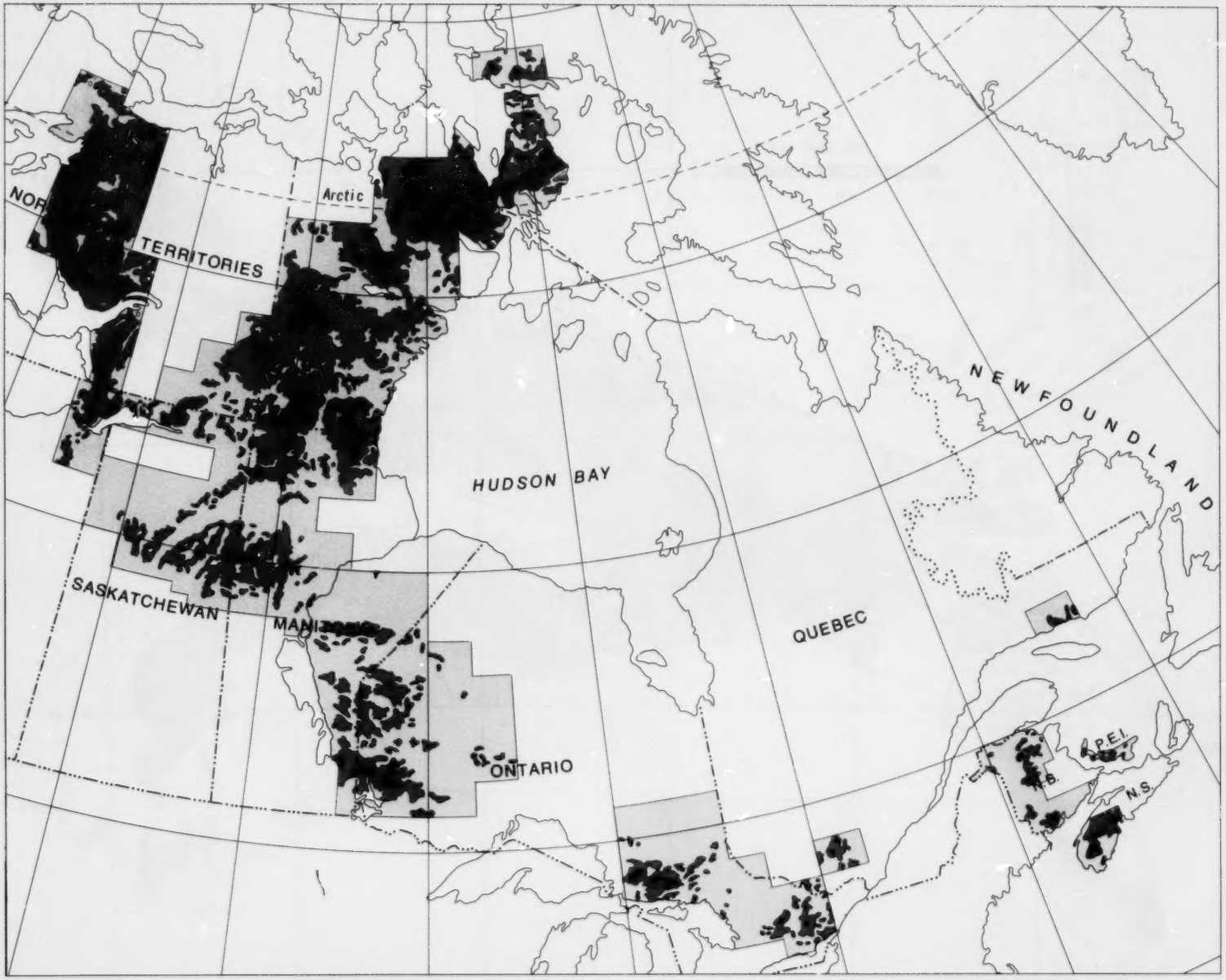

Figure 15. *Preliminary compilation of airborne data showing the distribution of uranium. The darker shades correspond to higher levels of uranium concentration.*

Table 10. Population data used in computing the average summer outdoor exposure rate from terrestrial radiation

Province	Population[1] (thousands)	Exposure Rate[2] ($\mu R \cdot h^{-1}$)
Newfoundland	568	2.40 ± 1.80
Nova Scotia	847	3.36 ± 1.66
Prince Edward Island	123	3.42 ± 1.41
Quebec	6 438	2.69 ± 1.67
Ontario	8 625	3.30 ± 1.99
Manitoba	1 026	5.78 ± 3.48
Saskatchewan	968	3.97 ± 2.43
Alberta	2 238	2.92 ± 2.30
Northwest Territories	46	5.69 ± 3.20
Population-weighted average for Canada		3.21 ± 2.00

[1]Population data from 1981 Canadian Census
[2]These results are uncorrected for the effects of vegetation (see text)

It is also necessary to consider whether the estimates for each province are representative of the areas where the majority of the population resides. For instance, most of the airborne data were gathered over the Canadian Shield whereas most of the population is concentrated in areas suitable for cultivation which are geologically different, mainly being flat-lying sedimentary rocks.

A detailed comparison of the Shield and sedimentary areas of southern Ontario was carried out using data published by Loijens and Grasty (1973). These data were used as base levels of radioactivity for an airborne gamma ray snow survey which covered a large part of the populated areas of southwestern Ontario as well as a significant area of the Shield. When allowance was made for the attenuation of the airborne signal by the forest cover of the Shield (estimated to be 15 per cent) no significant difference was found between the radiation levels on or off the Shield.

The similarity of the radiation levels of these two geologically different areas was somewhat unexpected as the Shield was originally believed to be more radioactive. However, further investigation showed that the clays and shales commonly found in southern Ontario have relatively high potassium contents, between 3 and 5 per cent (Guillet, 1977). In addition, although the Shield has some rocks such as granites and pegmatites which have above average radioactivity, these tend to be spatially restricted. To a large extent the Shield area of southern Ontario is composed of a variety of igneous and metamorphic rocks which are not particularly radioactive. Furthermore, the poor drainage of the Shield also produces large areas of water saturated soils which further reduces its level of radioactivity.

Additional confirmation of the similarity of the two areas may be found from the results presented in Table 7. The Pembroke Ontario map sheet (31F) lies totally within the Canadian Shield and has similar but slightly lower exposure rate than the adjacent map sheet (Kingston, 31C, Table 7), which is split roughly equally between the Canadian Shield and sedimentary rocks typical of populated areas in Ontario. These results strongly indicate that at least for Ontario the radioactivity levels of Table 7 are representative of the populated areas.

The Effect of Forest Cover

Another important factor to consider when calculating exposure rates is the effect of trees on the airborne measurements of gamma radiation, because they absorb gamma radiation from the ground. An additional complicating factor arises because the aircraft radar-altimeter is reflected from the forest canopy and not from the ground below the trees. The aircraft altimeter therefore will register an apparent altitude above the ground which is less than the true value. The error in the altitude will depend on the height of the trees and the density of the forest cover. Over a forested area, the effects of gamma ray attenuation and the radar-altimeter error both result in an estimate of ground radioactivity which is lower than the true value.

The quantity of bio-mass in a forest can vary widely. Rubin et al. (1979), in a study of the effects of vegetation on the uranium spectrum, reported that 50 per cent of forests in the United States have an above ground bio-mass between 0 and 3.5 $g \cdot cm^{-2}$. Gordon (1981) gave values between 1.0 and 1.6 $g \cdot cm^{-2}$ for three average stands of trees in Ontario; similar values would be expected in Quebec. Using a bio-mass value of 1.3 $g \cdot cm^{-2}$ and an air density of 0.001293 $g \cdot cm^{-3}$ this corresponds approximately to a 10 m equivalent layer of air. The error associated with the altimeter was estimated to be 10 m. In a typical forested area in Quebec or Ontario the aircraft is therefore flying at an equivalent elevation above ground which is around 20 m higher than registered by the radar altimeter.

Based on the attenuation of gamma radiation with aircraft altitude (Figure 3 and Equation 4), and using attenuation coefficients given by Glynn and Grasty (1980) 20 m of air will reduce the calculated potassium and thorium count rates and their associated concentrations by 16 and 13 per cent respectively. As potassium and thorium are the major contributors to the total exposure, the average summer outdoor exposure rates for Quebec and Ontario (Tables 7, 8) must be increased by approximately 15 per cent. Since most of the population is concentrated in these two provinces, this correction of 15 per cent must also be applied to the estimated population weighted summer outdoor exposure rate of 3.2 ± 2.0 $\mu R \cdot h^{-1}$ (Table 10) which results in an exposure rate from terrestrial radiation of 3.7 ± 2.3 $\mu R \cdot h^{-1}$.

ANNUAL OUTDOOR DOSE FROM TERRESTRIAL RADIATION

In calculating an average annual outdoor dose from terrestrial radiation it is necessary to consider that much of Canada is snow covered for several months each year. In addition significant soil moisture changes occur throughout the year which also affect the outdoor radiation levels.

The Effect of Snow

Snow reduces the radiation exposure at the surface of the ground. The attenuation of the radiation depends not on the depth of the snow but on its water content. This attenuation is the basis of an airborne technique to measure the water equivalent of the snow cover and has been widely used in various parts of the world (Kogan et al., 1971; Grasty, 1973). Because of the difference in the energy spectrum of the gamma radiation from potassium, uranium and thorium, the attenuation of the ground level exposure rate depends to some extent on the proportions of the three radioactive elements. Based on the variation of exposure rate with elevation above ground of typical granite composition, presented graphically by Lovborg and Kirkegaard (1975), 8 cm of water will reduce the exposure rate by approximately 50 per cent.

A large part of Canada is snow covered for several months each year. Since the data presented in this report were gathered in the summer months, the average annual outdoor exposure rate will be lower than shown in Table 7. In theory, to calculate the effect of snow, the average snow-water equivalent on the ground must be determined for each province whenever the amount of snow changes. This is because the exposure rate does not vary linearly with snow-water equivalent but approximates an exponential curve. The amount of snow on the ground, however, varies considerably from year to year; in addition, it has a relatively minor effect (20 per cent) on the exposure rate. We have assumed therefore that the average snow-water equivalent on the ground during the winter months can be averaged over an entire year and its effect need not be evaluated at different times throughout the winter.

Information on snowfall is readily available, however, data relating to the water content of the snow on the ground is limited. The Great Lakes/St. Lawrence Study Office of Environment Canada gathers snow-water equivalent information from a variety of sources each winter to predict the snow-water content of the Great Lakes drainage basin. Since most of the population of Canada resides in Quebec and Ontario (Table 10), data for the Great Lakes basin were used to compute the effect of snow on the outdoor exposure rate.

The data for the Great Lakes basin showed that for the first week of January, the drainage basin had a mean water-equivalent content of 41 mm for the period 1973 to 1981 inclusive. Together with the values for February and March of 71 and 74 mm respectively, this corresponds to a snow-water equivalent of 15.5 mm averaged over an entire year. No data were available for December and April. Tabulated data provided by Lovborg (Lovborg and Kirkegaard, 1975) showed that this 15.5 mm of water will reduce the exposure rate at ground level by 16 per cent. When an additional estimated reduction is made for the presence of snow in December and April the annual outdoor population weighted average exposure rate will be reduced by approximately 20 per cent from its measured summer value.

Seasonal Soil Moisture Variations

The results presented in this report show significant variations in radioactivity from area to area, mainly depending on the particular underlying geological formation. Individual radioactivity measurements, however, can vary significantly with time, mainly through changes in the moisture content of the soil. A 20 per cent increase in soil moisture (e.g. 20 to 40 per cent) is not uncommon and will in theory decrease the gamma radiation at the soil surface also by about 20 per cent (Equation 5). Variations of this magnitude have been observed in the gamma ray count rate from both potassium and thorium over the Breckenridge calibration strip (Fig. 4) which are undoubtedly related to soil moisture changes.

The effect of soil moisture on the gamma radiation from the uranium series is more complex than it is for potassium or thorium because a water-saturated soil can inhibit the emanation of radon thereby increasing its gamma ray activity. For our particular calibration strip the gamma ray activity from uranium can increase by almost 50 per cent when the soil becomes saturated (Fig. 5), whereas the potassium and thorium activities show about a 15 per cent decrease. The uranium series generally contributes only about 10 per cent to the total exposure rate (Table 7) and therefore the effect of large fluctuations in the activity from the uranium series does not have a great effect on the total exposure rate. In addition, the soil along the test strip is of clay composition, which is known to be a high emanator of radon (Barretto et al., 1972). In other areas with soils of more sandy composition, and lower emanation rates, the variation in gamma ray activity from the uranium decay series is expected to be less.

Table 11. Average monthly soil moisture values for the top 15 cm of soil in southern Ontario

Months	Soil Moisture (Per cent dry weight)	Number of Measurements
November to February [1]	39.4 ± 7.1	30
March [2]	49.9 ± 7.6	24
April	43.1 ± 8.1	23
May	40.3 ± 9.4	122
June	33.7 ± 10.3	196
July	29.8 ± 10.3	240
August	32.0 ± 10.3	237
September	30.4 ± 10.1	131
October	36.9 ± 9.3	83

[1] Average of November and December values
[2] Average of highest values of each site (saturated ground)

Since no data on the moisture content of the soil were obtained during the airborne data collection period, the effect of soil moisture puts a limit on the accuracy of any one particular airborne measurement. The airborne measurements represent many hundreds of days of flying and therefore the average exposure rate for Canada will closely represent the average soil moisture conditions over the summer months when the surveys were carried out. In the summer the soil will on average have a lower soil moisture content than for the remainder of the year.

To estimate the effect of seasonal soil moisture fluctuations on the calculated gamma ray exposure rates, we have analyzed over 1000 soil moisture measurements reported for 24 different sites in southern Ontario. These measurements were carried out principally during the growing season in the years 1966 to 1968 by the Ontario Agricultural College of the University of Guelph (Selirio et al., 1978).

Table 11 shows the monthly average soil moisture values for the top 15 cm of soil. The top layer of soil is the region of interest since most of the gamma radiation measured at the surface originates here. No data were available for the months of January, February, and March. We have assumed that the soil moisture content does not change in January and February from its December value because the ground is frozen. In March, the ground would normally be saturated because of snow-melt and the thawing ground. This saturation value was estimated from the average maximum soil moisture content of the 24 sites.

Considering the number of measurements involved, the results clearly show the soil moisture changes that occur throughout the year. Similar results have been obtained from water balance calculations carried out by the Atmospheric Environment Service of Environment Canada using 30 year mean air temperature data to determine potential evapotranspiration (Thornthwaite and Mather, 1957). Together with precipitation data, variations in the water stored in the soil were then calculated. The tabulated water balance data, measured as millimetres of water, were converted to soil moisture content, by making simple assumptions of generally observed maximum and minimum soil moisture values.

Table 12. Correction factors to be applied to summer outdoor exposure rates to derive annual values

Effect	Percentage Change
Attenuation by Snow	-20
Seasonal Soil Moisture Changes	- 5
Attenuation of Airborne Signal by Forest Cover	+15
Total Reduction = 13 per cent (1.15 x 0.95 x 0.80)	

Table 11 shows that in the four summer months from June to September, when most of the airborne surveys were carried out, the average soil moisture content is 31.5 per cent. This compares to an annual average of 37.8 per cent. Using equation (5) this change in soil moisture corresponds to a change in exposure rate of about 5 per cent. Consequently the summer exposure rate data (Tables 7 and 8) must be decreased by 5 per cent when average annual values are considered.

Calculation of average outdoor dose-equivalent

In computing an average annual outdoor dose-equivalent from terrestrial radiation, it is necessary to consider the effects described in the previous sections, the magnitudes of which are given in Table 12. This table shows that over an entire year the population weighted outdoor summer exposure rate of 3.2 ± 2.0 $\mu R \cdot h^{-1}$ (Table 10), as calculated directly from the airborne data, must be reduced by 13 per cent, yielding a new rate from terrestrial radiation of 2.8 ± 1.7 $\mu R \cdot h^{-1}$.

This average annual outdoor exposure rate can then be converted to an annual outdoor whole-body dose using a conversion factor of 0.6 $rad \cdot R^{-1}$. With an RBE value of 1 (Equation 3), the average annual outdoor dose-equivalent from terrestrial radiation was calculated as 150 ± 90 μSv (15 ± 9 mrem).

ADDITIONAL COMPONENTS OF OUTDOOR RADIATION DOSE

In estimating the average annual outdoor dose equivalent from all sources of natural radiation, three additional sources must be considered: cosmic radiation, airborne radioactivity, and the internal radioactivity of the body.

Cosmic Radiation

A large component of the radiation dose to the human population arises from high energy cosmic radiation entering the earth's atmosphere. The primary cosmic rays, mainly consisting of high energy protons, interact with atomic nuclei to produce electromagnetic radiation and secondary particles such as pions, muons, neutrons and electrons. Below an altitude of 5 km most of the radiation dose arises from muons, muon collision electrons, and muon decay electrons (O'Brien, 1972). A small non-ionizing component of the radiation dose arises from neutrons.

The cosmic ray intensity shows small fluctuations of about 5 per cent related to the phase of the 11 year solar cycle. It also varies to some extent with geomagnetic latitude because of the screening effect of the earth's magnetic field which is greater at the lower latitudes. Since the atmosphere attenuates the cosmic ray flux, the cosmic ray intensity increases with altitude, doubling approximately every 2000 m. Changes in barometric pressure and temperature and the associated differences in atmospheric attenuation also cause small fluctuations of a short-term nature. Solar flares can result in increases in cosmic ray activity. Solar cosmic rays, however, have relatively low energy and rarely cause any significant increase in the radiation dose at the earth's surface (International Commission on Radiological Protection, 1966).

Estimates of the cosmic radiation levels in Canada were derived from theoretical data published by O'Brien (1972) and O'Brien and McLaughlin (1972). These data, presented conveniently in the form of tables, show good agreement with experimental measurements of Neher (1967) and Lowder and Beck (1966) and the more recent measurements at the Environmental Measurements Laboratory in New York (Volchok et al., 1981). The rather high experimental values of George (1970), which are frequently incorporated into cosmic ray dose estimations (Oakley, 1972), are believed to be due to contamination from atomic weapons fallout (Liboff, 1972).

Population data from the 1981 Canadian census for 24 metropolitan areas representing 56 per cent of the population were used to derive the average longitude, latitude and elevation above sea level of the Canadian population. This was found to be at an elevation of 170 m, and located at 46°N and 88°W in Wisconsin, U.S.A.! From the position of the geomagnetic pole at 78°N and 69°W this position corresponds to a geomagnetic latitude of 57°N which is close to the 55°N for which theoretical data was calculated by O'Brien (1972).

At Canadian latitudes, Carmichael and Bercovitch (1969) have found that both the neutron and muon fluxes at sea level are independent of latitude to within 1 per cent. The worldwide surveys of Millikan and Neher in the early 1930s also found that north of 35°N the cosmic ray fluxes are constant over the entire North American continent (Millikan and Neher, 1936). Recent measurements reported by the Advisory Committee for Radiation Biology Aspects of the SST (1975) also showed very little variation of radiation dose for geomagnetic latitudes between 37° and 58°N at an altitude of 3 km. Consequently O'Brien's data at 55° can be used reliably to evaluate the population dose at different elevations in Canada. These data, representing the ionizing component of cosmic radiation, are presented in Figure 16 and are the mean of the tabulated values at solar minimum and solar maximum.

At sea level the dose-equivalent rate is approximately 290 $\mu Sv \cdot a^{-1}$ (29 $mrem \cdot a^{-1}$) but reaches a value as high as 430 $\mu Sv \cdot a^{-1}$ (43 $mrem \cdot a^{-1}$) for Banff, Alberta at an altitude of 1400 m. The result at sea level of 290 $\mu Sv \cdot a^{-1}$ (29 $mrem \cdot a^{-1}$) compares favourably with the values of 286 and 276 reported by Shamos and Liboff (1966) and Lowder and Beck (1966), respectively. The population weighted average cosmic ray ionization dose-equivalent rate for the mean population elevation of 170 m is 300 $\mu Sv \cdot a^{-1}$ (30 $mrem \cdot a^{-1}$), only slightly higher than the sea level value. It should be pointed out that these are outdoor values and do not include any shielding effect from buildings.

Figure 16 can also be used to estimate short term fluctuations due to barometric pressure changes. These pressure changes would generally not be more than about 2 per cent corresponding to an equivalent elevation change of around 150 m. Such an elevation change would vary the dose-equivalent by only ± 10 $\mu Sv \cdot a^{-1}$ (± 1 $mrem \cdot a^{-1}$). Temperature variations will cause fluctuations of a similar magnitude.

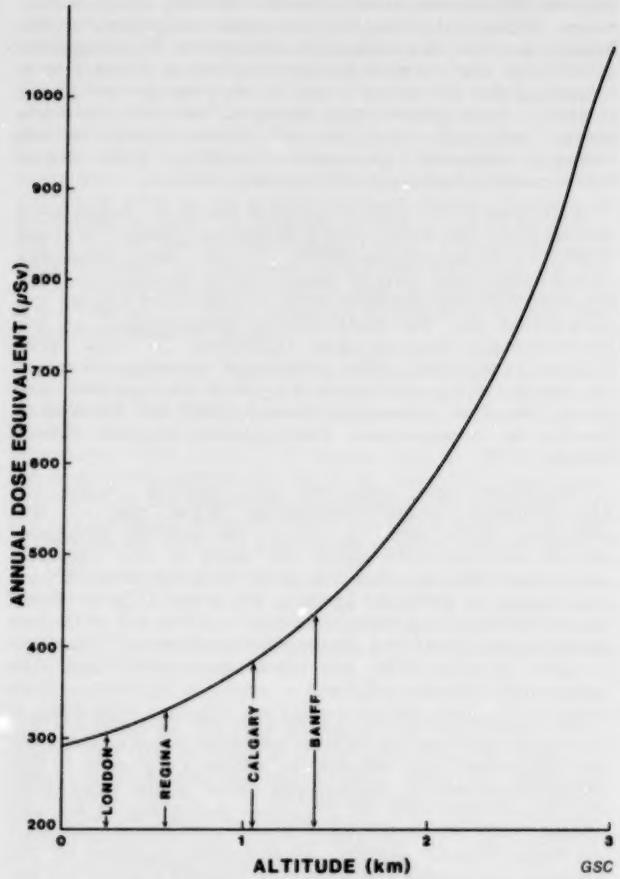

Figure 16. *Variation with altitude of the annual dose equivalent from the ionizing component of cosmic radiation.*

The neutron absorbed dose rate in air is small compared to that from charged particles. In tissue with a high proportion of hydrogen atoms, however, the neutron absorbed dose rate must be taken into account. For consistency, we have also adopted the calculated values of O'Brien and McLaughlin (1972) for the neutron dose rate at sea level. Their value of 22 $\mu Sv \cdot a^{-1}$ (2.2 $mrem \cdot a^{-1}$) is in good agreement with the experimental value of Hajnal et al. (1971) and also agrees closely with the figure adopted by UNSCEAR (1977).

The total outdoor dose-equivalent rate for all components of cosmic radiation is therefore estimated to be 320 $\mu Sv \cdot a^{-1}$ (32 $mrem \cdot a^{-1}$). This figure varies by about 5 per cent (± 15 $\mu Sv \cdot a^{-1}$ or ± 1.5 $mrem \cdot a^{-1}$) depending on the solar cycle. Similar short-term fluctuations of around 10 $\mu Sv \cdot a^{-1}$ (1 $mrem \cdot a^{-1}$), due to barometric pressure or temperature changes will also occur.

Airborne Radioactivity

Atmospheric radon daughter products also have a small contribution to the radiation dose at ground level. This contribution shows both seasonal and diurnal variations (Gold et al., 1964).

During the course of the routine airborne surveys, the Geological Survey has carried out many measurements of atmospheric background over lakes and large rivers. From these background measurements we have calculated that under unusual meteorological conditions, such as temperature inversions, the exposure rate from radon daughters can be as high as 2.0 $\mu R \cdot h^{-1}$. Analysis of data from Nova Scotia showed a mean exposure rate of 0.08 $\mu R \cdot h^{-1}$ with values reaching 0.34 $\mu R \cdot h^{-1}$. In these calculations the aircraft was assumed to be flying in an effectively infinite homogeneous source of radiation and therefore receiving the same radiation from above and below the aircraft. In this situation the exposure rate at ground level and also the counts that would be observed in the bismuth window at ground level will be half the value at the aircraft altitude. The ^{214}Bi window count rate can then be converted to an equivalent uranium concentration and associated exposure rate using the relationships indicated in Tables 3 and 4. We also calculated an average annual exposure rate of 0.07 $\mu R \cdot h^{-1}$ from radon concentration data presented by Gold et al. (1964) using the relationship between total body exposure and radon concentration given by Kocher (1980).

In comparison with terrestrial and cosmic radiation the contribution of airborne radon to the whole-body dose can be neglected. However, as previously pointed out, we are not considering the effects of alpha and beta particles which are significant in terms of radiation dose to the lungs and associated respiratory organs.

The Internal Radioactivity of the Body

This paper is principally concerned with external sources of radiation. However, a significant fraction of the radiation dose to the human body arises from naturally occurring radioactive elements principally ^{40}K, ^{14}C and to a small extent ^{87}Rb which are taken into the body. For the sake of completeness we include some basic data on these sources of internal radiation.

The dose to specific organs of the body can vary considerably. In this report only the average radiation dose received by the whole body is considered. These data have been taken directly from UNSCEAR (1977) and for more complete information on the dose received by various organs, the reader should refer to this report.

The major naturally occurring source of internal radiation dose is ^{40}K. The dose rate from ^{40}K can be calculated from its isotopic abundance and the concentration of potassium in human tissues. Similarly the dose from ^{87}Rb may be calculated from its concentration in various organs of the body and this has been carried out by the International Commission on Radiological Protection (1975) for the 'Reference Man'.

Some of the internal radiation dose also arises from ^{14}C which is produced from the capture of cosmogenic neutrons by ^{14}N and eventually taken into the body.

Table 13. Annual whole-body dose-equivalents from internal sources of radioactivity

Source	Annual Dose-Equivalent (μSv)
^{40}K	170
^{87}Rb	4
^{14}C	13
Total	187

The internal dose from all three radionuclides is presented in Table 13 which shows that ^{40}K is by far the greatest source of internal radiation dose.

Table 14 shows the average annual Canadian outdoor dose-equivalent from all sources of natural radiation to be 660 ± 90 μSv (66 ± 9 mrem).

ESTIMATION OF ANNUAL DOSE-EQUIVALENT

The Effects of Buildings

In estimating the average annual dose-equivalent, it is necessary to consider that most people spend a large percentage of their time indoors where the building material acts as both a source of radioactivity and a shield. Estimates of indoor dose can in theory be derived from the radioactivity of the various building materials and their configuration. We have followed, however, the simpler procedure adopted by UNSCEAR (1977) and the National Council on Radiation Protection (1975) which is to estimate the average indoor gamma ray dose from the outdoor terrestrial value using a conversion factor which at least makes some allowance for the effect of buildings.

Our justification for using the outside terrestrial values to derive an inside value assumes the local origin of most building materials. In Canada, the majority of single family dwellings have concrete floors or basements which are generally underlain by a thick gravel bed originating from a local quarry. In addition, the concrete itself is to a large extent composed of sand and gravel of local origin. Concrete is also the major building material for most apartment blocks or office buildings. Figure 12 shows that the exposure rate from a rock outcrop is closely related to the exposure rate of the surface material nearby. Consequently the radioactivity of the surface material in any area would be related to the radioactivity of the concrete used in the buildings. Even bricks used in buildings of masonry construction or as facing are generally derived from clays of local origin (Guillet, 1977).

Radiation levels in apartment blocks, multi-storey office buildings, or buildings of masonry construction are significantly higher than for buildings of wood-frame construction where the building materials (wood and plaster) are generally low in radioactivity compared to brick and concrete. These multi-story buildings could also be expected to have higher radiation levels purely from geometrical considerations, because the lower floors are receiving radiation from building material in all directions rather than just from below. In estimating the radiation levels inside a building, the shielding effects of the walls and the floors must be considered.

At 12.5 cm above the ground approximately 75 per cent of the radiation exposure originates from a circular area on the ground 3 m in diameter (Lovborg et al., 1979). Specifically for this paper, and using the same computer program, Lovborg has calculated that at a height of 1 m, 67 per cent of the radiation comes from a circular area 8 m in diameter. This diameter of 8 m is representative of the width of a typical house. At a height of 3 m above the ground only 35 per cent originates from the same circular area. Consequently on the ground floor of most buildings, away from the walls, only a small percentage of the inside radiation exposure can originate from sources outside the house, even if there are no walls present. At ground level, the attenuation characteristics of the walls therefore have very little bearing on the exposure inside. At higher floor levels, where the radiation is received from a much larger area, transmission of the outside radiation through the walls may become significant. This will depend on such things as the elevation above the ground, the floor area, and the attenuation characteristics of the walls.

Table 14. Average annual Canadian whole-body[1] outdoor dose-equivalent from natural sources of radiation

Source	Dose Equivalent (μSv)
Cosmic Rays	320 ± 30
Terrestrial Radiation	150 ± 90
Internal Radioactivity	190
Total	660 ± 90

[1] The same values are estimated for the lungs, gonads and red bone marrow

Inside a wood-frame building the attenuation of the radiation originating beneath the floor by material used in the floor construction has a significant effect on the radiation exposure. A wooden floor with its associated supporting joists would typically have a mass per unit area of about 3 $g \cdot cm^{-2}$ which would reduce the radiation from beneath the floor by 20 to 25 per cent (Beck, 1972). On the upper floors the radiation from material beneath the ground floor would be attenuated even further by material in the additional floors. This increased attenuation would to some extent be compensated by increased radiation from the outside and we would therefore expect a value of around 0.75 to be the minimum indoor-to-outdoor ratio for these types of buildings. Any additional radiation from building material such as brick facing would increase this value.

From an analysis of published data, UNSCEAR (1977) concluded that the world average exposure rate from terrestrial radiation is 18 per cent higher than it is outside. This reflects the fact that the average person spends a large percentage of his time in apartment blocks or office buildings where the ratio of indoor-to-outdoor exposure rate is estimated to be 1.3. The National Council on Radiation Protection (1975) concluded that in the United States the indoor exposure rates from natural gamma radiation are on average 20 per cent lower than they are outside. Because of these substantially different results we have re-analyzed the data used to derive these values.

In some instances (e.g. Lowder and Condon, 1965), the data used to derive the indoor-to-outdoor ratios were gathered at a time when fallout from atomic weapons testing was a substantial fraction of the outdoor exposure rate. Now that fallout is only a small component of the outdoor exposure rate some of the earlier results with low indoor-to-outdoor ratios are no longer valid and must be modified accordingly.

Based on the fallout data presented by Lowder and Condon (1965), mostly for wood-frame buildings, the indoor-to-outdoor ratio will now have increased from 0.70 to 0.86. Similarly Ohlsen's (1969) data for buildings of varied construction will increase from 0.78 to 0.86. More recent data from Norway (Stranden, 1977), with negligible contribution from fallout, gave a value of 0.95 for the indoor-to-outdoor ratio for wood-frame buildings. These values are consistent with our simple calculations and we have therefore taken an indoor-to-outdoor ratio of 0.90 as being typical of buildings of wood-frame construction. From a limited analysis of published information we have accepted the UNSCEAR (1977) figure of 1.3 as the ratio of the indoor radiation levels to the outside terrestrial values for apartment blocks and office buildings.

Calculation of the annual dose-equivalent

Based on statistics from the 1981 Canadian Census we estimate that 25 per cent of the population lives in apartment blocks of more than two storeys where the indoor-to-outdoor ratio is 1.3. The remaining 75 per cent live in buildings where the indoor-to-outdoor ratio is 0.90. In calculating the annual dose-equivalent we will assume that an average of 16 hours of every day are spent in a home, 6 hours at work in an office block or in a similar building where the indoor-to-outdoor ratio is 1.3 and 2 hours outside. With these assumptions we find that for the 22 hours of each day spent indoors, 55 per cent [75 x 16/22] of the time is spent in buildings where the indoor-to-outdoor ratio is 0.90 and the remaining 45 per cent in apartment blocks or office buildings where the indoor-to-outdoor ratio is 1.3. This gives an average indoor-to-outdoor ratio of 1.08.

The population weighted summer outdoor exposure rate from terrestrial radiation as calculated previously is $3.7 \pm 2.3\ \mu R\,h^{-1}$. Using the indoor-to-outdoor conversion factor of 1.08 we arrive at a figure of $4.0 \pm 2.5\ \mu R\,h^{-1}$ for the average indoor gamma ray exposure rate. No correction has been applied for snow or soil moisture variations throughout the year since the conversion factor of 1.08 was derived from measurements which would normally be taken in the summer months when the ground was dry. Using equations 2 and 3, the indoor exposure rate of $4.0 \pm 2.5\ \mu R\,h^{-1}$ corresponds to an annual indoor dose-equivalent of $210 \pm 130\ \mu Sv$ (21 ± 12 mrem).

Table 14 shows that the average outdoor dose-equivalent from terrestrial radiation is $150 \pm 90\ \mu Sv$ (15 ± 9 mrem). If 2 hours of each day are spent outdoors and 22 hours indoors where the annual dose-equivalent from external gamma radiation is $210 \pm 130\ \mu Sv$ (21 ± 13 mrem) then the average annual whole-body dose-equivalent from external gamma radiation is essentially controlled by the indoor dose-equivalent and is also $210 \pm 130\ \mu Sv$ (21 ± 13 mrem).

From the relationship between cosmic ray dose-equivalent and elevation above sea level (Fig. 26) structural shielding of density 200 to 300 $g\,cm^{-2}$ will reduce the outdoor cosmic ray intensity by 50 per cent. This amount of shielding is not unreasonable for a large apartment block or office building. The National Council on Radiation Protection and Measurement (1975) have estimated 10 per cent to be an average attenuation factor for outdoor cosmic radiation. We have used this figure of 10 per cent which reduces the annual cosmic ray dose-equivalent (Table 14) to $290 \pm 30\ \mu Sv$ (29 ± 3 mrem). Table 15 shows our estimated average annual whole-body dose-equivalent from all sources of natural radiation to be $690 \pm 130\ \mu Sv$ (69 ± 13 mrem).

Although the effect of buildings must remain one of the largest sources of error in estimating the annual radiation dose, it should be noted that terrestrial radiation contributes only about 35 per cent of the annual Canadian whole-body dose (Table 15). Consequently an extreme error of 30 per cent in the conversion factor between indoor and outdoor exposure will result in an error of only 10 per cent in the estimated annual dose.

Table 15. Estimated average annual Canadian whole-body[1] dose-equivalents from natural sources of radiation

Source	Dose-equivalent (μSv)
Cosmic Rays	290 ± 30
External Gamma Radiation	210 ± 130
Internal Radioactivity	190
Total	690 ± 130

[1] The same values are estimated for the lungs, gonads and red bone marrow

DISCUSSION OF RESULTS

UNSCEAR (1977) estimated the world average terrestrial outdoor absorbed dose rate in air to be $0.045\ Gy\,h^{-1}$ ($4.5\ \mu rad\,h^{-1}$). From equation (1) this corresponds to an exposure rate of $5.2\ \mu R\,h^{-1}$. The UNSCEAR value was based on large area surveys from ten different countries for which the original exposure rates range from 4.1 to $10.2\ \mu R\,h^{-1}$. However, the results of Ohlsen (1969) for East Germany and Herbst (1964) for Switzerland included some contribution from atomic weapons fallout. Figure 17 shows the natural terrestrial exposure rates of the ten countries after removal of the reported fallout contributions of 1.0 and $3.1\ \mu R\,h^{-1}$ for East Germany and Switzerland respectively. The values shown in Figure 17 were obtained from the original published data which in some instances differ from the values reported by UNSCEAR (1977).

The outdoor terrestrial summer value for Canada of $4.4 \pm 2.9\ \mu R\,h^{-1}$ (also shown in Fig. 17) is less than the estimated world average and is one of the lowest of all the countries. The summer value was selected for comparison, since the annual value includes the effect of snow and soil moisture variations which have not been incorporated in the countrywide data reported by UNSCEAR (1977). Using the summer values we are therefore better able to compare the actual radioactivity of the ground itself.

The fact that Canada has a low average level of radioactivity is to be expected because large areas are covered with geologically old Precambrian rocks. Both heat flow data and geochemical studies strongly indicate a general decrease in radioactivity with increasing geological age which can be explained in terms of a simple model of crustal evolution.

There is substantial evidence for a general decrease of continental heat flow with the age of crustal material, the older Precambrian Shield showing very low heat flows (Vitorello and Pollack, 1980; Hamza and Verma, 1969; etc.).

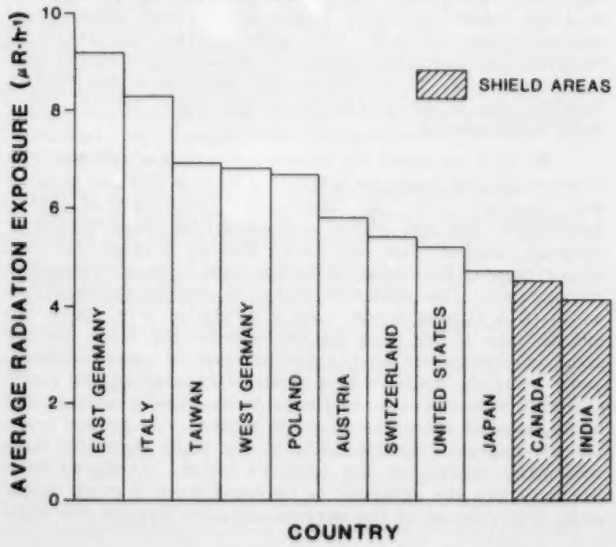

Figure 17. *Outdoor exposure rates for some countries.*

This heat is generated by the decay of radioactive material from within the crust. Additional sources of heat originate from deep beneath the continent, in its roots, and perhaps from the earth's core. From a knowledge of the surface radioactivity, the observed heat flow is found to be too low to be explained by a uniformly radioactive crust. It can only be explained by a decrease of radioactivity with depth below the crustal surface (Lachenbruch, 1968). In time this surface is eroded, removing the more radioactive material, and exposing material with a lower radioactivity. Based on a simple model for this decrease of radioactivity with depth, Vitorello and Pollack (1980) have estimated that the heat flow originating from within the continental crust can vary by as much as a factor of two, depending on the age of the rocks. The radioactivity of the surface rocks would be expected to show a similar variation. It should be emphasized that the relation of the age of the rock to its radioactivity is only a general one. Rao and Jessop (1975) have shown that the radiation levels and associated heat flow are functions not only of the age of the rock but also of the rock type (Table 9).

From an analysis of thousands of rock samples Eade and Fahrig (1971) have found that within the Canadian Shield rocks of different ages vary chemically, the younger rocks being higher in potassium, uranium and thorium. They also explain this chemical difference through erosion of a zoned crust in which the radioactive elements decrease with depth. The erosion of a zoned crust would result in the enrichment of the radioactive elements in younger sedimentary basins. Consequently, any crust subsequently evolved from these sediments would be higher in radioactivity relative to older rocks exposed as a result of erosion. Rogers (1978) has also studied the variation in composition of the crust with time and found that younger Shield areas have higher concentrations of potassium (and presumably uranium and thorium) than older crusts.

The European countries listed in Figure 27 are underlain by rocks which, for the most part, are much younger than those in the areas surveyed in Canada. These countries show the highest exposure levels. India and Canada are the only countries reported by UNSCEAR (1977) which have large areas covered by very much older Shield material. India and Canada show the two lowest exposure rates. Italy and East Germany are covered with some of the youngest rocks, and have the highest levels of radioactivity. These results would be expected with a crust which decreases in radioactivity with depth. It is also interesting to note that the older Precambrian granites of Nova Scotia are lower in radioactivity compared to the younger Devonian Carboniferous granites (Fig. 23, 24).

Table 7 shows that the outdoor terrestrial summer exposure rate of 4.4 $\mu R \cdot h^{-1}$ is made up 48 per cent from potassium, 43 per cent from the thorium series and the remaining 9 per cent from the uranium series. The continental crust is estimated by Taylor (1964) to have average concentrations of 2.1 per cent potassium, 2.7 ppm uranium and 9.6 ppm thorium (Table 9). Based on these concentrations and on their relationship to exposure rate (Table 4), potassium and thorium should both contribute approximately 40 per cent to the total exposure rate with the remaining 20 per cent originating from uranium. Our measured contribution of 9 per cent from the uranium series is significantly lower than the value calculated from the crustal average. This low percentage would be expected if there were a significant loss of radon and its associated gamma ray emitting daughter products from the soil surface.

Airborne measurements over the Breckenridge calibration strip have shown considerable variation in gamma ray activity from the uranium series (Fig. 5). The highest activity was observed when the soil was saturated with water. Under these conditions the emanation of radon from the ground would be reduced, allowing the gamma ray activity of the radon daughter products to increase. When the attenuation effect of water in the soil is considered the airborne measurements indicate a radon loss of about 40 per cent when the soil is relatively dry. A comparison of summer field gamma ray spectrometer measurements and sealed can laboratory assays (Table 2) shows a radon loss of around 45 per cent for the Breckenridge calibration range. Radon losses of this magnitude are consistent with the measurements of Barretto et al. (1972) for clay soils similar to those of the Breckenridge area. More recent airborne measurements taken under a variety of different soil conditions have shown that radon losses of around 40 per cent are typical of large areas of Canada.

Because of radon loss from the soil surface, the ^{214}Bi gamma ray activity in the summer months may be far from equilibrium with the uranium (or radium) in the soil, and the equivalent uranium concentration calculated from the airborne gamma ray data may be considerably lower than the true ground concentration of chemical uranium. Any conclusions relating to the absolute abundances of uranium or radium in the soil must therefore take into consideration radon loss from the soil surface.

SUMMARY AND CONCLUSIONS

Listed below is a summary of observations made in this paper and the conclusions drawn:

1. Ground level exposure rates can be determined by airborne gamma ray spectrometry from the measured surface concentrations of potassium, uranium, and thorium.
2. Airborne measurements of ground level concentrations were confirmed using calibrated portable gamma ray spectrometers over 24 test sites.
3. Ground level exposure rates calculated from airborne data recorded over an airborne calibration range were confirmed by measurements with a Reuter-Stokes Ionization chamber.
4. Airborne surveys flown over 33 areas, representing approximately 900 000 individual measurements, were used to compile information on average ground level exposure rates in Canada.
5. Large areas of anomalously high radioactivity in northern Manitoba and the Northwest Territories were generally found to be related to granitic rocks.
6. The increased radioactivity of northern Canada results to some extent from its lack of vegetation, and high percentage of rock outcrop.
7. The lowest radioactive areas were found to be associated with the Athabasca sandstone.
8. Outdoor summer exposure rates from potassium, uranium and thorium for the 33 study areas, had an average of 4.4 ± 2.9 $\mu R \cdot h^{-1}$. This result does not include the attenuation of the airborne signal by forest cover, which in some areas, will reduce the calculated exposure rate as much as 15 per cent.
9. Of this 4.4 $\mu R \cdot h^{-1}$, 48 per cent originated from potassium, 43 per cent from the thorium series, and the remaining 9 per cent from the uranium series. The contribution from uranium is lower than would be expected from crustal abundance estimates because of a significant loss of radon from the soil surface.

10. When attenuation of the airborne signal by forest cover is considered, the population weighted average summer outdoor exposure rate from terrestrial radiation, is found to be 3.7 ± 2.3 $\mu R \cdot h^{-1}$. This is considerably less than the world average of 5.2 $\mu R \cdot h^{-1}$ estimated by UNSCEAR (1977) but can be explained by erosion of a geologically old continental crust in which the radioactivity decreases with depth.

11. When the effects of seasonal variations of soil moisture, and the attenuation of the ground radiation by snow are considered, the population weighted outdoor exposure rate from terrestrial radiation is found to be 2.8 ± 1.7 $\mu R \cdot h^{-1}$ averaged over an entire year.

12. Using a conversion factor of 0.6 $rad \cdot R^{-1}$, the average annual Canadian outdoor whole-body dose-equivalent from terrestrial radiation is found to be 150 ± 90 μSv (15 ± 90 mrem).

13. Additional components of outdoor annual dose-equivalent arise from cosmic radiation (320 ± 30 μSv or 32 ± 3 mrem) and the internal radioactivity of the body (190 μSv or 19 mrem) which give a total outdoor annual value of 660 ± 90 μSv (66 ± 9 mrem).

14. Based on a comparison of indoor and outdoor values from worldwide published data, the average annual Canadian whole-body dose-equivalent from all sources of natural radiation is estimated to be 690 ± 130 μSv (69 ± 13 mrem).

ACKNOWLEDGMENTS

This work could not have been carried out without the co-operation of many people. We should like to thank Q. Bristow and personnel in his Instrumentation Research and Development Section who designed and maintained the two gamma ray spectrometers. We are also grateful to R.G. McGregor and W.B. Walker of the Department of Health and Welfare for carrying out the ionization chamber measurements.

Much of the information for this paper was gathered from scientists in a variety of disciplines. We would like to thank the following:

S.N. Edey of the Department of Agriculture, P. Louie of the Atmospheric Environment Service, T. Carroll of the U.S. National Weather Service and D.M. Brown of the University of Guelph for soil moisture data;

D.F. Witherspoon of the Great Lakes-St. Lawrence Study Office of Environment Canada for snow-water equivalent data;

P.A. Camfield of the Earth Physics Branch of the Department of Energy, Mines and Resources for information relating to the earth's magnetic field and A.S. Judge of the same organization for information relating to heat flow.

We are particularly grateful to L. Lovborg of the Danish Atomic Energy Commission, Riso who, specifically for this paper, calculated the exposure rate from circular sources of different sizes. In addition he provided information on the relationship between exposure rate and soil moisture content.

K.A. Richardson, P.G. Killeen and J. Howieson made valuable suggestions for improving the original manuscript.

It should be recognized that the airborne program was initially organized and developed by A.G. Darnley who together with K.A. Richardson are largely responsible for its success.

REFERENCES

Advisory Committee For Radiation Biology Aspects of the SST
1975: Cosmic radiation exposure in supersonic and subsonic flights; Aviation, Space, and Environmental Medicine, v. 48, no. 9, p. 1170-1185.

Barretto, P.M.C., Clark, R.B., and Adams, J.A.S.
1972: Physical characteristics of radon-222 emanation from rocks, soils and minerals: its relation to temperature and alpha dose; Proceedings of the Second International Symposium on the Natural Radiation Environment, Houston, Texas. ed. J.A.S. Adams, W.M. Lowder, and T.F. Gesell, United States Department of Commerce, Springfield, Virginia, p. 731-740.

Beck, H.L.
1972: The physics of environmental gamma radiation fields; Proceedings of the Second International Symposium on the Natural Radiation Environment, Houston, Texas. ed. J.A.S. Adams, W.M. Lowder, and T.F. Gesell, United States Department of Commerce, Springfield, Virginia, p. 101-133.

Beck, H. and de Planque, G.
1968: The radiation field in air due to distributed gamma ray sources in the ground; United States Atomic Energy Commission, New York. Health and Safety Laboratory Report HASL-195.

Beck, H.L., Decampo, J., and Gogolak, C.
1972: In situ Ge(Li) and NaI(Tl) gammma-ray spectrometry; United States Atomic Energy Commission, New York. Health and Safety Laboratory Report, HASL-258.

Bristow, Q.
1979: A gamma ray spectrometry system for airborne geological research; in Current Research, Part C, Geological Survey of Canada, Paper 79-1C, p. 55-61.

Burson, Z.G.
1973: Airborne surveys of terrestrial gamma radiation in environmental research; IEEE Transactions on Nuclear Science, v. NS-21(1), p. 558-571.

Carmichael, H. and Bercovitch, M.
1969: Analysis of IQSY cosmic ray survey measurements; Canadian Journal of Physics, v. 47, p. 2073-2093.

Charbonneau, B.W.
1982: Radiometric study of three radioactive granites in the Canadian Shield: Elliot Lake, Ontario, Fort Smith and Fury and Hecla, N.W.T.; in Uranium in Granites, ed. Y.T. Maurice, Geological Survey of Canada, Paper 81-23, p. 91-99.

Charbonneau, B.W. and Darnley, A.G.
1970: A test strip for calibration of airborne gamma ray spectrometers; in Report of Activities, Geological Survey of Canada, Paper 70-1, Part B, p. 27-32.

Charbonneau, B.W., Killeen, P.G., Carson, J.M., Cameron, G.W., and Richardson, K.A.
1976: Significance of radioelement concentration measurements made by airborne gamma-ray spectrometry over the Canadian Shield; in Exploration for Uranium Ore Deposits, International Atomic Energy Agency, Vienna, p. 35-53.

Darnley, A.G.
1970: Airborne gamma-ray spectrometry; Canadian Institute of Mining and Metallurgy, Transactions, v. 73, p. 20-29.

1976: The Canadian Uranium Reconnaissance Program; Paper presented to the American Nuclear Society, Washington, D.C., November 1976.

Darnley, A.G. and Fleet, M.
1968: Evaluation of airborne gamma-ray spectrometry in the Bancroft and Elliot Lake areas of Ontario, Canada; in Proceedings of the Fifth Symposium on Remote Sensing of Environment, University of Michigan, p. 833-853.

Darnley, A.G., Bristow, Q., and Donhoffer, D.K.
1969: Airborne gamma-ray spectrometer experiments over the Canadian Shield; in Nuclear Techniques and Mineral Resources, International Atomic Agency, Vienna, p. 163-186.

Eade, K.E. and Fahrig, W.F.
1971: Geochemical evolutionary trends of continental plates; a preliminary study of the Canadian Shield; Geological Survey of Canada, Bulletin 179.

Geodata International Inc.
1977: Lake Mead dynamic test range for calibration of airborne gamma radiation measuring systems; United States Energy Research and Development Agency, Report GJBX46(77).

George, M.J.
1970: New data on the absolute cosmic-ray ionization in the lower atmosphere; Journal of Geophysical Research, v. 75, p. 3693-3705.

Glynn, J.E. and Grasty, R.L.
1980: A calibration procedure for airborne gamma ray snow surveys; Proceedings of the Western Snow Conference, Laramie, Wyoming, April 15-17, 1980.

Gold, S., Barkhau, H.W., Shleien, B., and Kahn, B.
1964: Measurement of naturally occurring radionuclides in air; The Natural Radiation Environment, ed. J.A.S. Adams and T.F. Gesell, University of Chicago Press, p. 369-382.

Gordon, A.G.
1981: Impacts of harvesting on nutrient cycling in the boreal mixedwood forest; Proceedings Boreal Mixedwood Symposium, O-P-9, April 1981, p. 121-140.

Grasty, R.L.
1973: Snow-water equivalent measurement using material gamma emission; Nordic Hydrology, v. 4, p. 1-16.

1975: Atmospheric absorption of 2.62 MeV gamma-ray photons emitted from the ground; Geophysics, v. 40(6), p. 1058-1065.

1976: A calibration procedure for an airborne gamma-ray spectrometer; Geological Survey of Canada, Paper 76-16, p. 1-9.

Grasty, R.L. and Charbonneau, B.W.
1974: Gamma-ray spectrometer calibration facilities; in Report of Activities, Part B, Geological Survey of Canada, Paper 74-1B, p. 69-71.

Grasty, R.L. and Darnley, A.G.
1971: The calibration of gamma-ray spectrometers for ground and airborne use; Geological Survey of Canada, Paper 71-17, 27 p.

Guillet, G.R.
1977: Clay and shale deposits of Ontario; Ministry of Natural Resources, Ontario Geological Survey Mineral Deposits Circular MDC 15.

Hajnal, F., McLaughlin, J.E., Weinstein, M.S., and O'Brien, K.
1971: 1970 sea level cosmic ray neutron measurements; United States Atomic Energy Commission, New York, Health and Safety Laboratory Report HASL-241.

Hamza, V.M. and Verma, R.K.
1969: The relationship of heat flow with age of basement rocks; Bulletin Volcanologiques, Tome XXXIII - 1, p. 123-152.

Herbst, W.
1964: Investigations of environmental radiation and its variability; The Natural Radiation Environment. ed. J.A.S. Adams and T.F. Gesell, University of Chicago Press, Chicago, p. 781-796.

International Commission on Radiological Protection
1966: Task Group on the biological effects of high-energy radiations, radiobiological aspects of the supersonic transport; Health Physics, v. 12, p. 209-226.

1975: Report of the Task Group on Reference Man.; ICRP Publication 23, Pergamon Press, 480 p.

Killeen, P.G.
1979: Gamma ray spectrometric methods in uranium exploration - application and interpretation; in Geophysics and Geochemistry in the Search for Metallic Ores, Geological Survey of Canada, Economic Geology Report 31, p. 163-229.

Kirkegaard, P.
1972: Double-P_1 calculation of gamma-ray transport in semi-infinite media; Danish Atomic Energy Commission, Riso Report M-1460.

Kirkegaard, P. and Lovborg, L.
1980: Transport of terrestrial gamma radiation in plane semi-infinite geometry; Journal of Computational Physics, v. 36, p. 20-34.

Kocher, D.C.
1980: Dose-rate conversion factors for external exposure to photon and electron radiation from radionuclides occurring in routine releases from nuclear fuel cycle facilities; Health Physics, v. 38, p. 543-621.

Kogan, R.M., Nazarov, I.M., and Fridman, SH.D.
1971: Gamma spectrometry of natural environments and formations; Israel Program for Scientific Translations, Jerusalem.

Lachenbruch, A.H.
1968: Preliminary geothermal model of the Sierra Nevada; Journal of Geophysical Research, v. 73, p. 6977-6989.

Liboff, A.R.
1972: Cosmic ray ionization in the lower atmosphere, Proceedings of the Second International Symposium on The Natural Radiation Environment, ed. J.A.S. Adams, W.M. Lowder, and T.F. Gesell, United States Department of Commerce, Springfield, Virginia, p. 35-67.

Loijens, H.S. and Grasty, R.L.
1973: Airborne measurements of snow-water equivalent using natural gamma radiation over Southern Ontario, 1972-1973; Scientific Series No. 34, Water Resource Branch, Environment Canada, Ottawa, 21 p.

Lovborg, L. and Kirkegaard, P.
1974: Response of 3" x 3" NaI(Tl) detectors to terrestrial gamma radiation; Nuclear Instruments and Methods 121, p. 239-251.

1975: Numerical evaluation of the natural gamma radiation field at aerial survey heights; Danish Atomic Energy Commission, Riso Report 317.

Lovborg, L., Botter-Jensen, L., Kirkegaard, P., and Christiansen, E.M.
1979: Monitoring of natural soil radioactivity with portable gamma-ray spectrometers; Nuclear Instruments and Methods 167, p. 341-348.

Lowder, W.M. and Beck, H.L.
1966: Cosmic-ray ionization in the lower atmosphere; Journal of Geophysical Research, v. 71, p. 4661-4668.

Lowder, W.M. and Condon, W.J.
1965: Measurement of the exposure of human populations to environmental radiation; Nature, v. 206, p. 658-662.

Millikan, R.A. and Neher, H.V.
1936: A precision world survey of sea-level cosmic-ray intensities; Physical Review, v. 50, p. 15-24.

National Council on Radiation Protection and Measurement
1975: National background radiation in the United States; National Council on Radiation Protection and Measurements, Report NCRP 45.

Neher, H.V.
1967: Cosmic-ray particles that changed from 1954 to 1958 to 1965; Journal of Geophysical Research, v. 72, p. 1527-1539.

Oakley, D.T.
1972: Natural radiation exposure in the United States; United States Environmental Protection Agency, Washington Report ORP/SID 72-1.

O'Brien, K.
1972: The cosmic ray field at ground level; Proceedings of the Second International Symposium on the Natural Radiation Environment, Houston, Texas, ed. J.A.S. Adams, W.M. Lowder, and T.F. Gesell, United States Department of Commerce, Springfield, Virginia, p. 15-54.

1978: Human dose from radiation of terrestrial origin; Proceedings of the Third International Symposium on the Natural Radiation Environment, Houston, Texas, ed. T.F. Gesell, and W.M. Lowder, Technical Information Centre, United States Dept. of Commerce, Springfield, Virginia, p. 1163-1210.

O'Brien, K. and McLaughlin, J.E.
1972: The radiation dose to man from galactic cosmic rays; Health Physics, v. 22, p. 225-232.

Ohlsen, H.
1969: Determination of the mean population burden from natural external radiation in the Soviet Zone of Germany; Staatliche Zentralle fur Strahlenschutz, report SZS-14/69, Berlin; also United States Atomic Energy Commisison Translation Report AEC-tr-7216.

Perttunen, M.
1977: The lithologic relation between till and bedrock in the region of Hameenlinna, Southern Finland; Geological Survey of Finland, Bulletin 291, 68 p.

Pitkin, J.A.
1968: Airborne measurements of terrestrial radioactivity as an aid to geological mapping; United States Geological Survey, Professional Paper 516-F, p. 29.

Rao, R.U.M. and Jessop, A.M.
1975: A comparison of the thermal characters of shields; Canadian Journal of Earth Sciences, v. 12, p. 347-360.

Rogers, J.J.W.
1978: Inferred composition of early Archaean crust and variation in crustal composition through time; Proceedings of the Symposium on Archaean Geochemistry, held in Hyderabad, India, November 15-17, 1977; ed. B.F. Windley, and S.M. Naqvi, Elsevier, New York, p. 25-39.

Rubin, R.M., Price, J.H., and Wells, M.B.
1979: Effects of vegetation on the energy and angular distribution of uranium daughter gamma rays at an altitude of 121.9 meters; U.S. Energy Research and Development Agency Report GJBX-55(80).

Selirio, I.S., Brown, D.M., and King, K.M.
1978: Soil moisture observations in Southern Ontario, 1966-68; Department of Land Resource Science, University of Guelph, Technical Memo 78-2, 44 p.

Shamos, M.H. and Liboff, A.R.
1966: A new measurement of the intensity of cosmic ray ionization at sea level; Journal of Geophysical Research, v. 71, p. 4651-4659.

Shilts, W.W.
1976: Glacial till and mineral exploration; in Glacial Till, An Interdisciplinary Study, ed. R.F. Legget, Royal Society of Canada, Special Publication 12, p. 205-224.

Stranden, E.
1977: Population doses from environmental gamma radiation in Norway; Health Physics, v. 33, p. 319-323.

Stromswold, D.C.
1978: Monitoring of the airport calibration pads at Walker Field, Grand Junction, Colorado for long-term radiation variations; United States Department of Energy Report GJBX-99(78).

Taylor, S.R.
1964: Abundance of chemical elements in the continental crust: a new table; Geochimica Cosmochimica Acta, v. 28, p. 1273-1285.

Thornthwaite, C.W. and Mather, J.R.
1957: Instructions and tables for computing potential evapotranspiration and the water balance; C.W. Thornthwaite Associates, Laboratory of Climatology, Centerton, New Jersey Publications in Climatology, Vol. X, No. 3.

UNSCEAR
1977: Sources and effects of ionizing radiation; United Nations Scientific Committee on the Effects of Atomic Radiation 1977 Report to the General Assembly, with annexes, United Nations, New York.

Vitorello, I. and Pollack, H.N.
1980: On the variation of continental heat flow with age and the thermal evolution of continents; Journal of Geophysical Research, v. 85, no. B2, p. 983-995.

Volchok, H.L. and staff members of the laboratory
1981: 1980 Environmental Measurements Laboratory Annual Report, EML 392, United States Department of Energy.

Ward, D.L.
1978: Construction of calibration facility United States Walker Field, Grand Junction, Colorado; Energy Research and Development Agency, Report GJBX-37(78).

APPENDIX

Distribution of exposure rates for areas across Canada as listed in Tables 6, 7 and 8

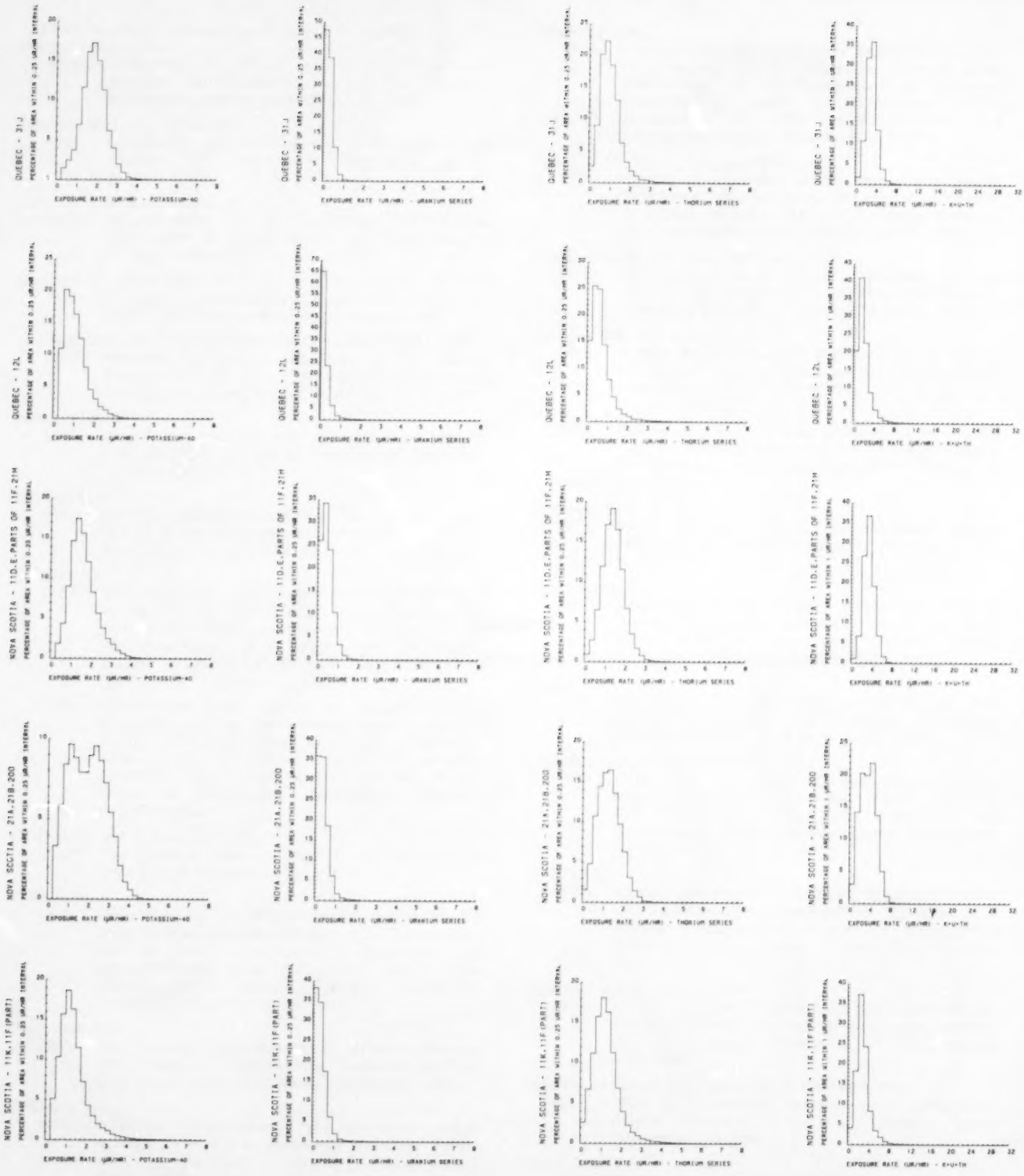
QUEBEC - 31J
QUEBEC - 12L
NOVA SCOTIA - 11D,E,PARTS OF 11F,21H
NOVA SCOTIA - 21A,21B,20D
NOVA SCOTIA - 11K,11F(PART)
PERCENTAGE OF AREA WITHIN 0.25 UR/HR INTERVAL
PERCENTAGE OF AREA WITHIN 1 UR/HR INTERVAL
EXPOSURE RATE (UR/HR) - POTASSIUM-40
EXPOSURE RATE (UR/HR) - URANIUM SERIES
EXPOSURE RATE (UR/HR) - THORIUM SERIES
EXPOSURE RATE (UR/HR) - K+U+TH

Figure A1. *Distribution of radiation exposure rates for areas in Nova Scotia and Quebec.*

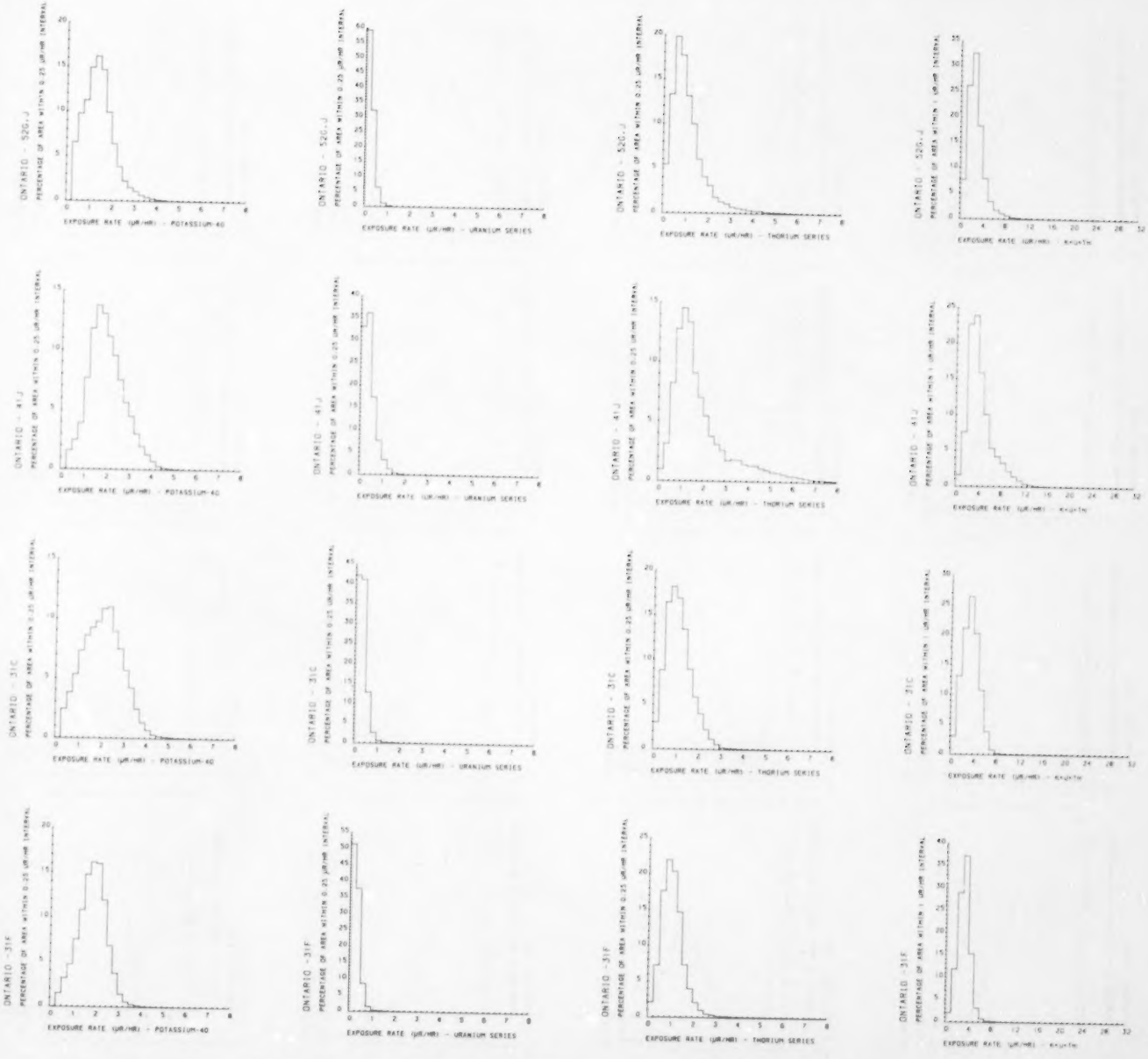
ONTARIO - 520-J
ONTARIO - 41-J
ONTARIO - 31C
ONTARIO - 31F
PERCENTAGE OF AREA WITHIN 0.25 UR/HR INTERVAL
EXPOSURE RATE (UR/HR) - POTASSIUM-40
EXPOSURE RATE (UR/HR) - URANIUM SERIES
EXPOSURE RATE (UR/HR) - THORIUM SERIES

Figure A2. *Distribution of radiation exposure rates for areas in Ontario.*

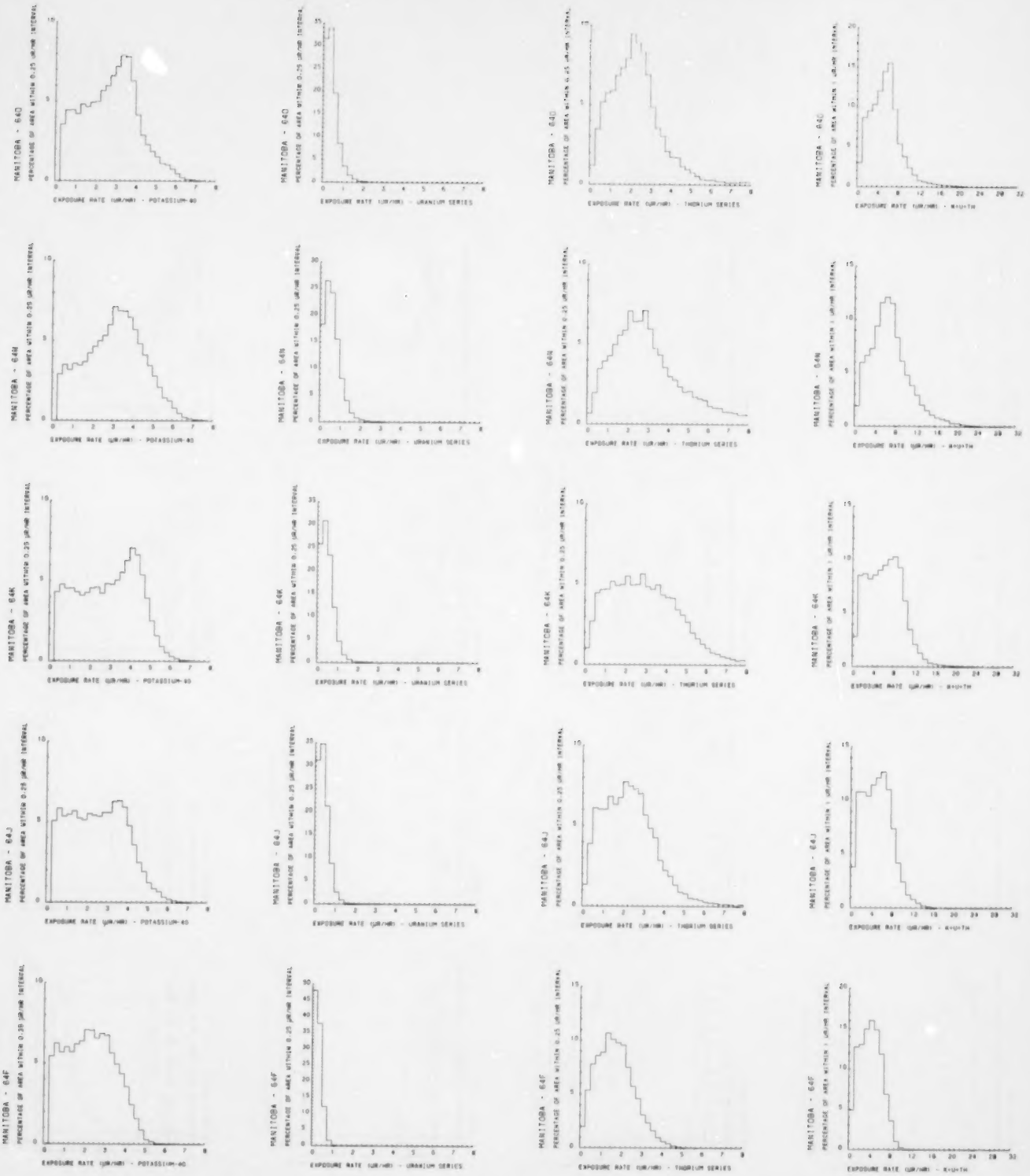

Figure A3. *Distribution of radiation exposure rates for areas in Manitoba.*

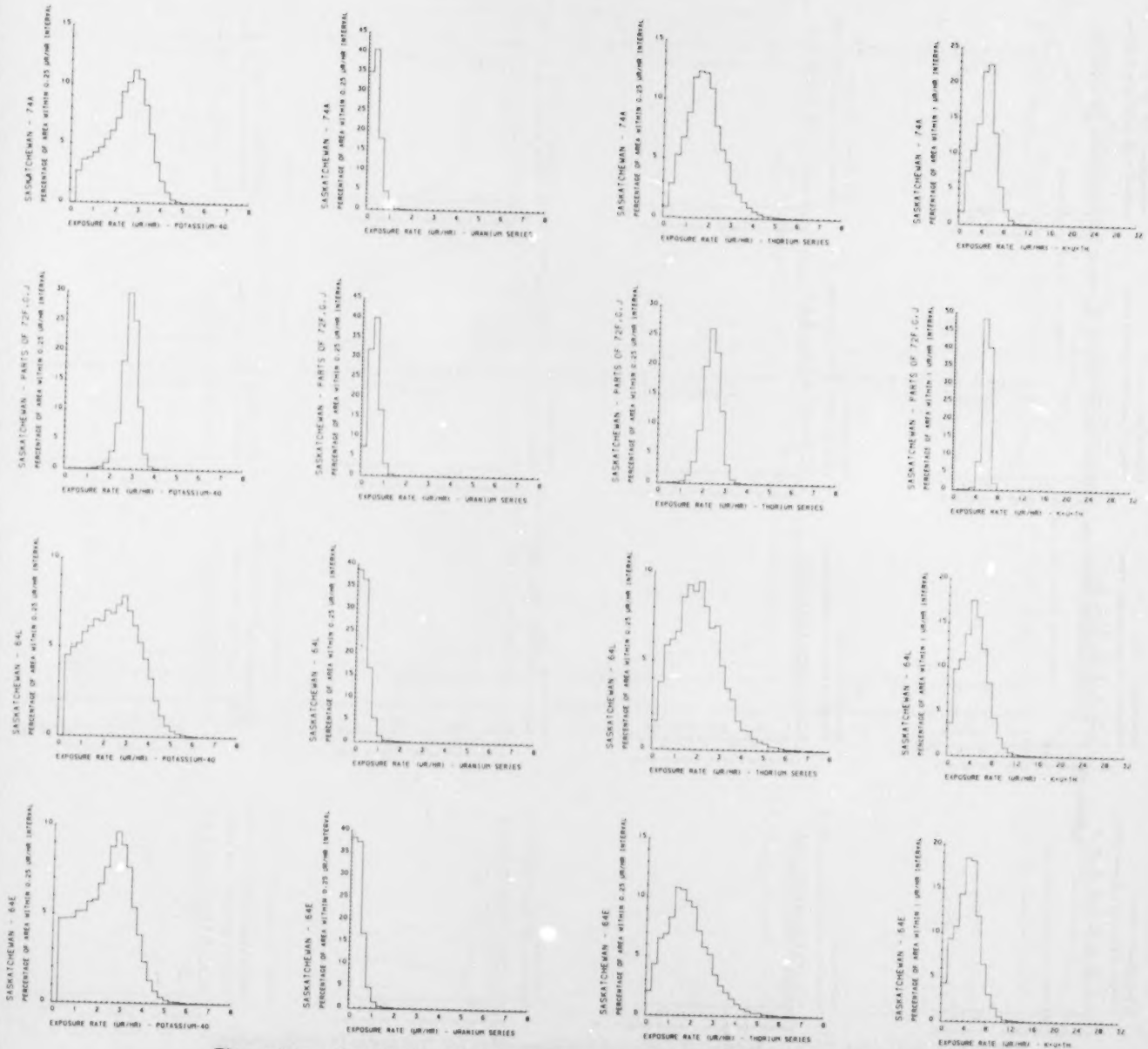
SASKATCHEWAN - 74A
PERCENTAGE OF AREA WITHIN 0.25 UR/HR INTERVAL
EXPOSURE RATE (UR/HR) - POTASSIUM-40
SASKATCHEWAN - 74A
EXPOSURE RATE (UR/HR) - URANIUM SERIES
SASKATCHEWAN - 74A
EXPOSURE RATE (UR/HR) - THORIUM SERIES
SASKATCHEWAN - 74A
SASKATCHEWAN - PARTS OF 72F,G,J
SASKATCHEWAN - 64L
SASKATCHEWAN - 64E

Figure A4. *Distribution of radiation exposure rates for four areas in Saskatchewan.*

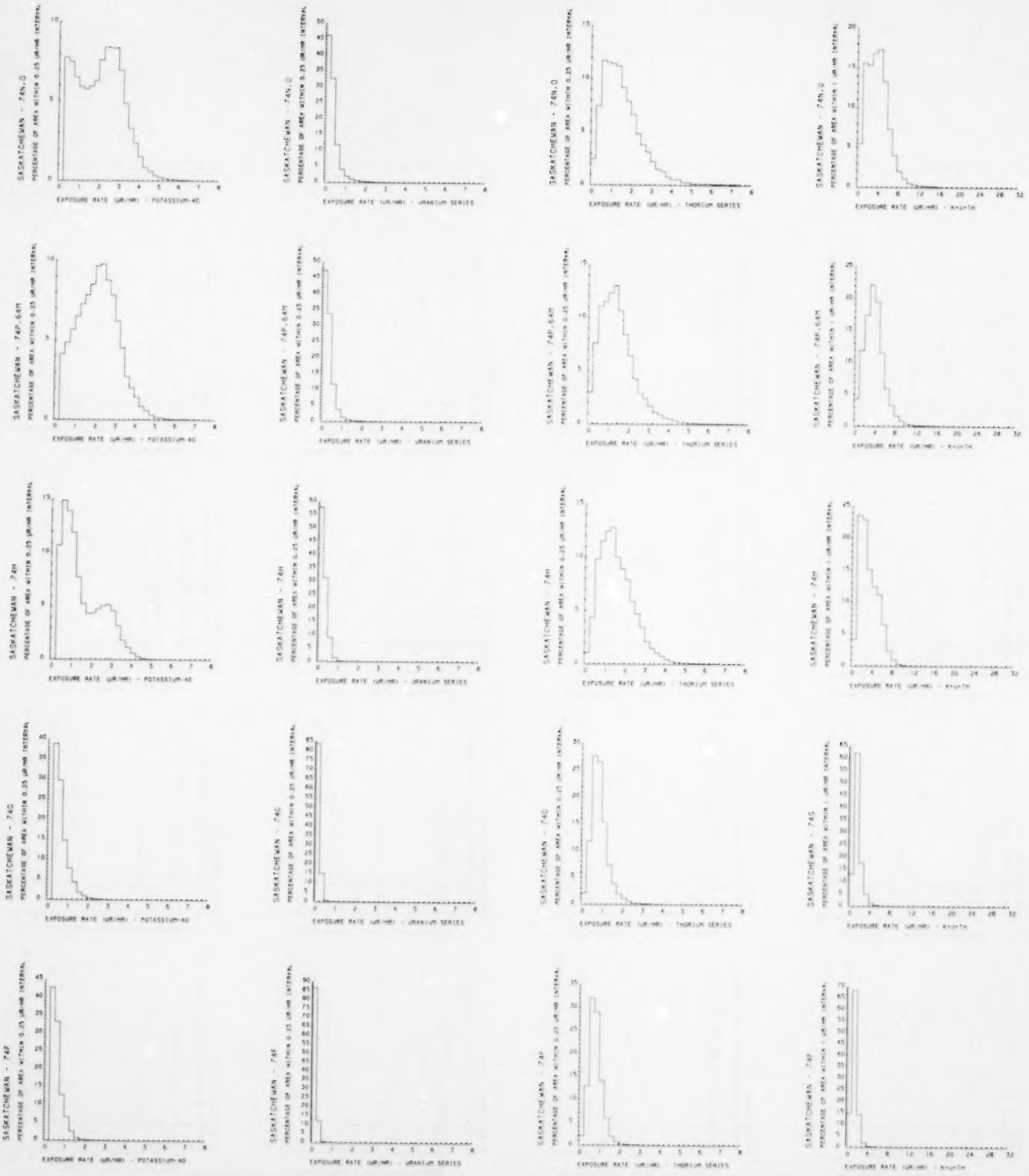

Figure A5. *Distribution of radiation exposure rates for five areas in Saskatchewan.*

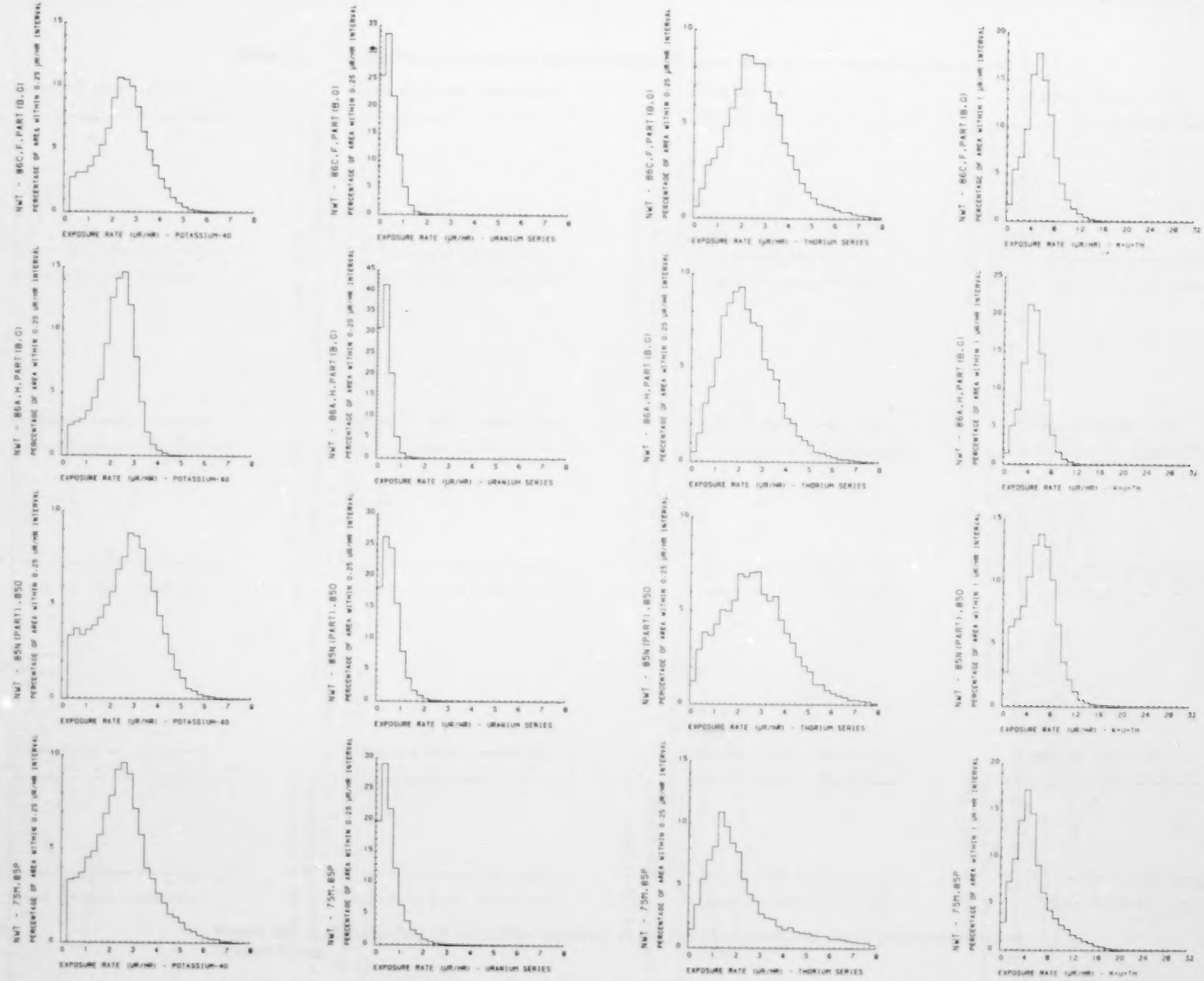
NWT - 86C.F.PART(B.C)
NWT - 86A.H.PART(B.C)
NWT - 85N(PART).85O
NWT - 75M.85P
PERCENTAGE OF AREA WITHIN 0.25 UR/HR INTERVAL
PERCENTAGE OF AREA WITHIN 1 UR/HR INTERVAL
EXPOSURE RATE (UR/HR) - POTASSIUM-40
EXPOSURE RATE (UR/HR) - URANIUM SERIES
EXPOSURE RATE (UR/HR) - THORIUM SERIES
EXPOSURE RATE (UR/HR) - K+U+TH

Figure A6. *Distribution of radiation exposure rates for four areas in the Northwest Territories.*

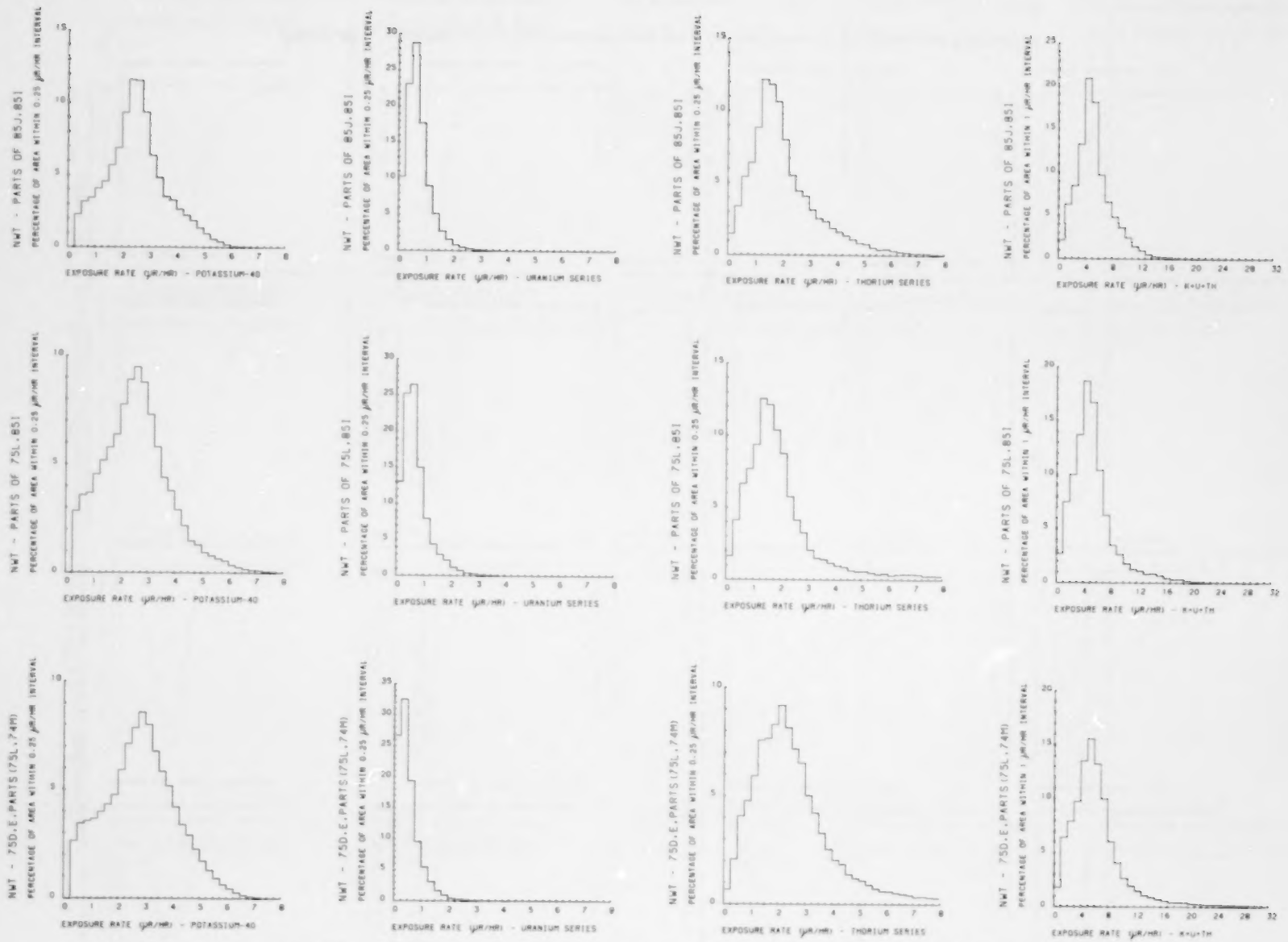

Figure A7. *Distribution of radiation exposure rates for three areas in the Northwest Territories.*

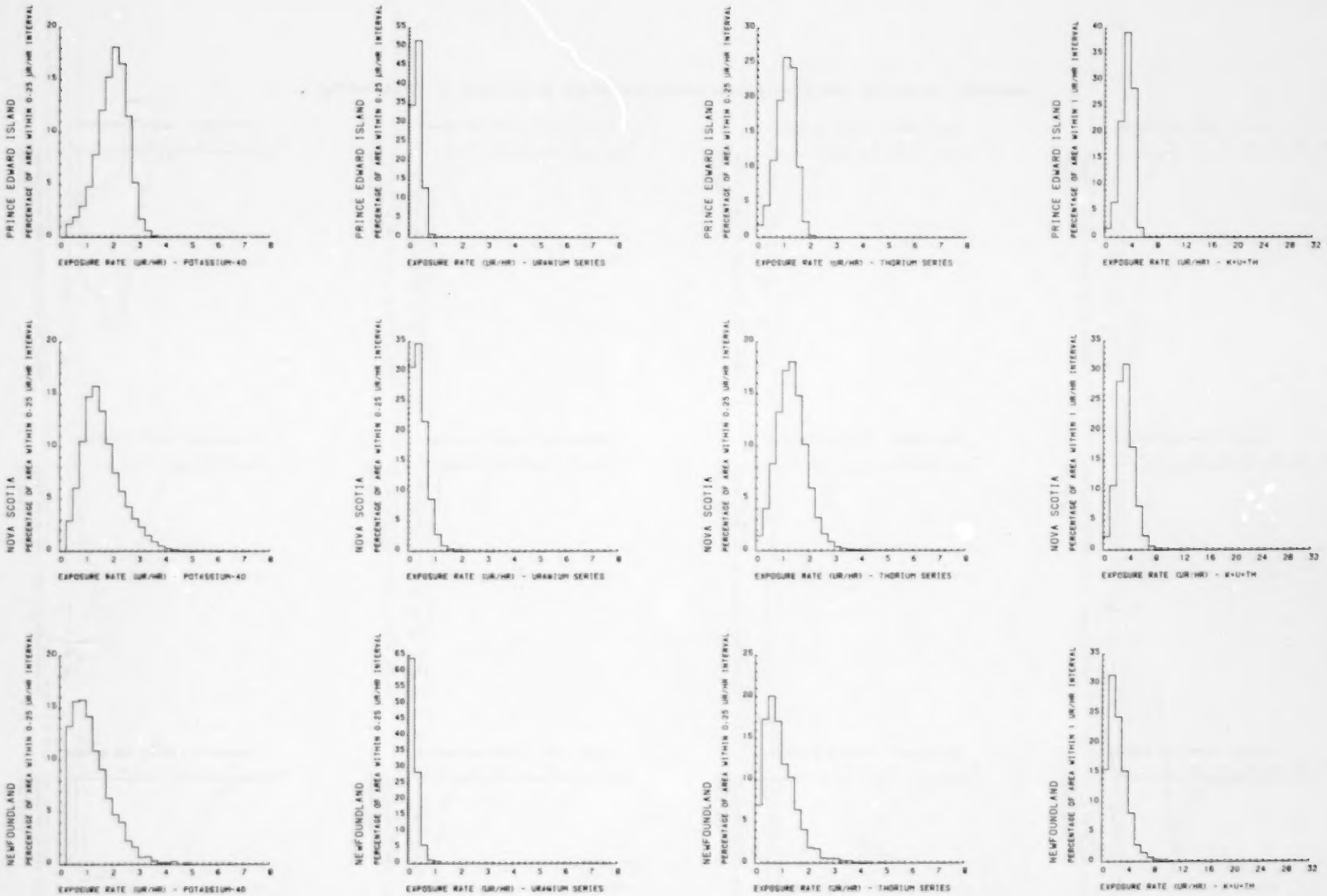
PRINCE EDWARD ISLAND
NOVA SCOTIA
NEWFOUNDLAND
PERCENTAGE OF AREA WITHIN 0.25 UR/HR INTERVAL
EXPOSURE RATE (UR/HR) - POTASSIUM-40
EXPOSURE RATE (UR/HR) - URANIUM SERIES
EXPOSURE RATE (UR/HR) - THORIUM SERIES
EXPOSURE RATE (UR/HR) - K+U+TH

Figure A8. *Distribution of radiation exposure rates for Newfoundland, Nova Scotia and Prince Edward Island.*

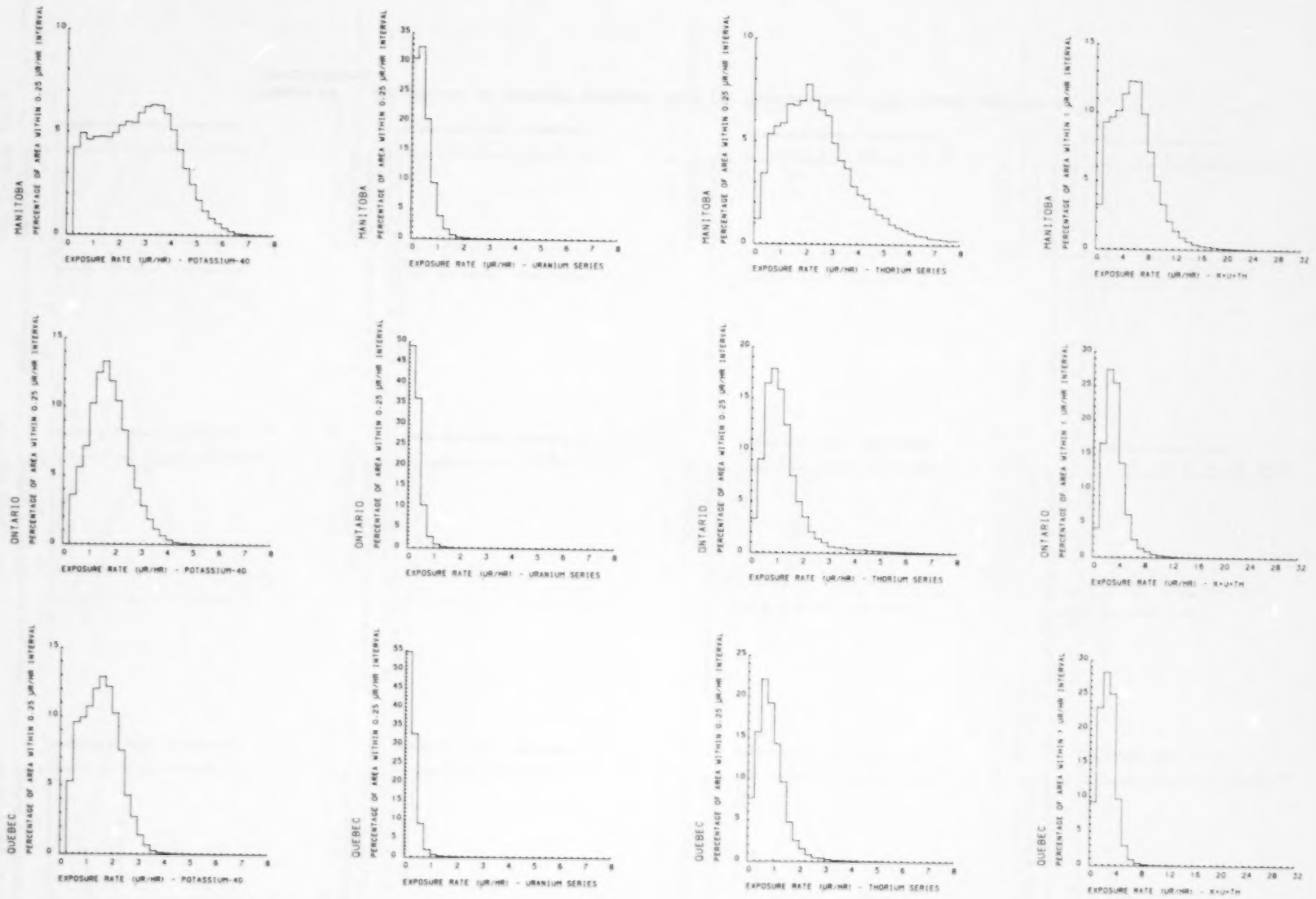

Figure A9. *Distribution of radiation exposure rates for Quebec, Ontario and Manitoba.*

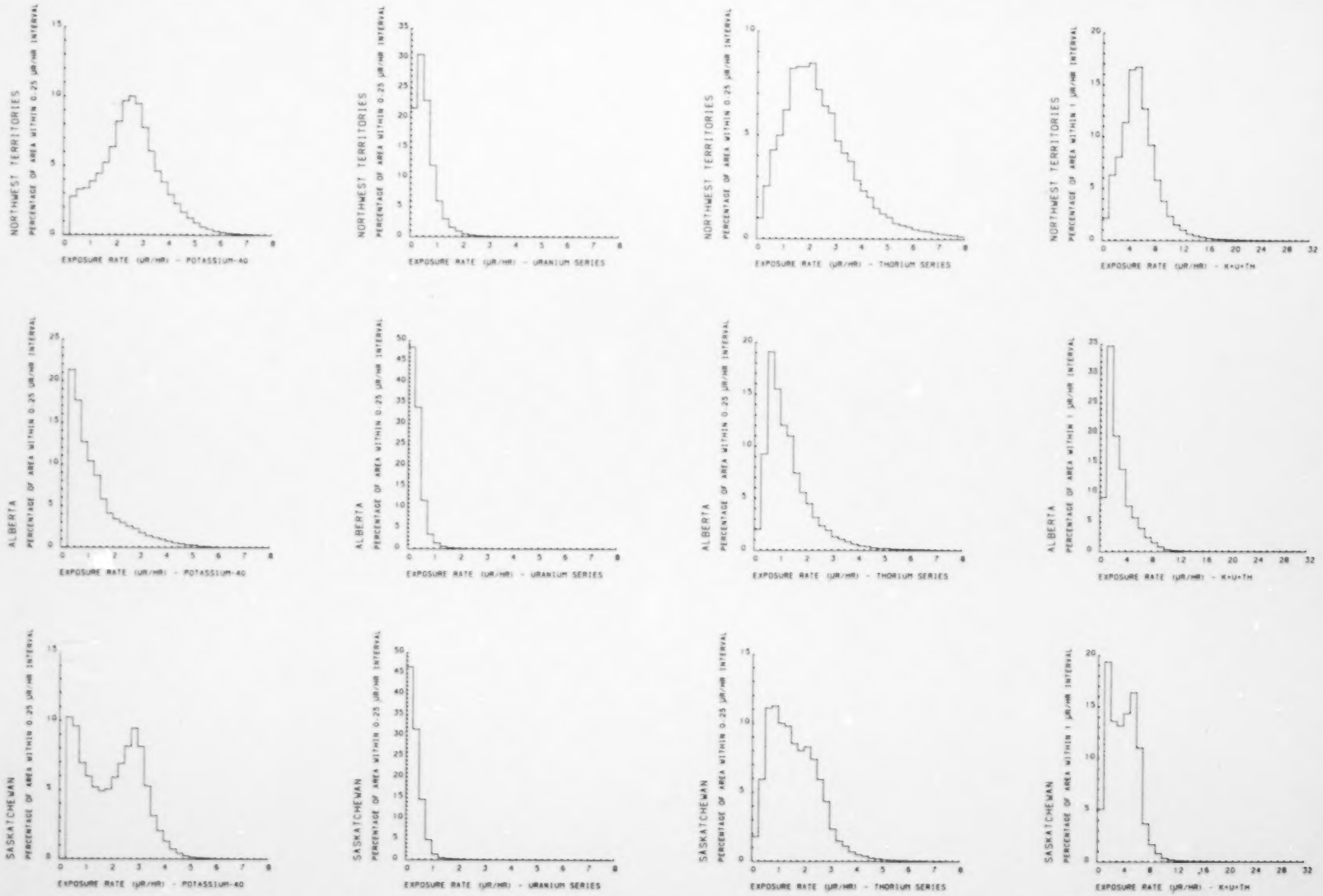
NORTHWEST TERRITORIES
PERCENTAGE OF AREA WITHIN 0.25 µR/HR INTERVAL
EXPOSURE RATE (µR/HR) - POTASSIUM-40
EXPOSURE RATE (µR/HR) - URANIUM SERIES
EXPOSURE RATE (µR/HR) - THORIUM SERIES
PERCENTAGE OF AREA WITHIN 1 µR/HR INTERVAL
EXPOSURE RATE (µR/HR) - K+U+TH
ALBERTA
SASKATCHEWAN

Figure A10. *Distribution of radiation exposure rates for Saskatchewan, Alberta and the Northwest Territories.*

Energy, Mines and Resources Canada

Énergie, Mines et Ressources Canada